Research Article

Simulating Grassland Prescribed Fires Using Experimental Approaches

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ABSTRACT

Small-scale fire approaches, like burn boxes, burn tables, and propane burners, are often used to facilitate experimental control over fire and allow greater replication. We compared characteristics of grassland prescribed fires to three experimental approaches to determine if these approaches simulate prescribed fires. We conducted prescribed fires during the growing and dormant season to compare with burn box, burn table, and propane prong approaches. Burn box and burn table approaches used additional timothy (*Phleum* spp. L.) hay for a fuel source, while the propane prong used propane to burn *in situ* and greenhouse-grown plants. We collected temperature data with thermocouples to determine time-temperature profiles, maximum temperatures, heat durations (time above 60 °C), and heat dosages (the product of time and temperature above 60 °C). Fires produced by burn box, burn table, and prescribed fires had similarly shaped time-temperature profiles, but propane prong fires produced different curves with a longer duration near the maximum temperature. Burn box and burn table approaches had the highest heat dosages because timothy hay

RESUMEN

Los fuegos experimentales a pequeña escala, como las quemas en caja, en mesas de quema y con quemadores de propano, son frecuentemente utilizados para controlar experimentalmente el fuego y permitir más repeticiones de los mismos. Nosotros comparamos las características de las quemas prescritas en pastizales realizadas durante las estaciones de crecimiento y de reposo con tres ensayos experimentales que involucraron quemas en cajas, en mesas de quema y usando clavijas de propano. Para las cajas y las mesas de quema, se utilizó paja de timote (*Phleum* spp. L.) como fuente de combustible, mientras que para los ensayos con clavijas de propano se utilizó propano para hacer quemas *in situ* y también sobre plantas producidas en invernaderos. Nosotros tomamos datos de temperaturas con termocuplas para determinar perfiles de temperatura, temperaturas máximas, duración del calor (duración de las temperaturas por sobre los 60 °C), y de dosis de calor (el producto de la duración y la temperatura por encima de los 60 °C). Los fuegos producidos en las cajas de quema, en las mesas de quema y en las quemas prescritas presentaron perfiles similares en cuanto a duración y temperatura, aunque los fuegos realizados con clavijas de propano produjeron diferentes curvas, con una duración mayor cerca del máximo de temperatura. Los ensayos en cajas de quema y en mesas de quema tuvieron las dosis más altas de calor porque la paja del timote se quemó compleburned completely compared to *in situ* vegetation in prescribed fires. To simulate prescribed fires, propane rates should be regulated—either increased or decreased—to produce time-temperature profiles consistent with prescribed fires. Moreover, approaches using added hay often result in higher heat dosages and may require decreased fuel loading to match research objectives.

tamente en comparación con la vegetación *in situ* de las quemas prescritas. Para simular quemas prescritas, las tasas de propano deberían ser reguladas—aumentándolas o disminuyéndolas—para producir perfiles de duración y temperatura consistentes con las propias quemas. Más aún, los ensayos con paja producen a menudo altas dosis de calor y pueden requerir menor cantidad de carga de combustible para que así puedan encuadrarse en los objetivos de investigación.

Keywords: fire methodology, fuel, grasslands, heat dosage, prescribed burn, rangelands, simulation, time-temperature curve

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INTRODUCTION

Climate, fire, and grazing formed and maintain grasslands in North America (Anderson 2006), but land fragmentation (Higgins 1984) and fire suppression have limited the extent and use of fire since European settlement (Umbanhowar 1996). Recently, demands for fire research have increased as managers and researchers work to restore pre-settlement disturbance regimes and ecological processes (Fuhlendorf *et al.* 2009). Although fire research activity has increased in most grassland biomes, there are still many unanswered questions relating to ecological effects of fire. Fire is an important ecological process that can be effectively implemented for management after the fire regime has been assessed over a wide range of conditions and landscapes. However, most research fails to measure fire characteristics and burning conditions, which can contribute to variable results when quantifying fire effects (Fuhlendorf *et al.* 2011).

Experimental approaches may be suitable substitutes to prescribed fires when examining fire effects on vegetation and soils. However, there are inherent differences when using wildfires, prescribed fires, or other approaches to study fire ecology (Sullivan *et al.* 2013). Therefore, one approach may not be suitable for all research questions. To increase replicates and experimental control, fire ecology researchers often conduct fires on a smaller scale compared to wildfires and prescribed fires (Sullivan *et al.* 2013). Research plots typically vary in size from several square meters (Redmann *et al*. 1993, Waterman and Vermeire 2011) to several hectares (Whisenant and Uresk 1989, Smart *et al*. 2013). Researchers make small plots in the field by creating breaks and barriers with back burns (Biondini *et al.* 1989, Belsky 1992) and metal sheeting (Sharrow and Wright 1977, White and Currie 1983, Whitford and Steinberger 2012). Most small plots still maintain many of the same features, such as weather interactions, as larger prescribed fires. However, weather interactions can be eliminated in the field by using propane burners made of stainless steel barrels and installed jets that burn enclosed *in situ* vegetation or individual plants (Britton and Wright 1979).

In addition to the approaches presented above, several other methods can be used to simulate fire or heat that move studies from the field to a laboratory setting. Wind tunnels are commonly used to study fire spread and heat transfer under different fuel characteristics with controlled wind speeds and temperatures (Rothermel and Anderson 1966, Lui *et al.* 2014). Wind tunnels are usually large, free-standing structures that burn harvested biomass, unlike field approaches, which consume living plants rooted in a substrate. Fuel beds or burn tables can also use harvested biomass (Weise *et al.* 2005, Weir and Limb 2013) or rooted plants in an open area (Limb *et al.* 2011). Other approaches, such as furnaces, use indirect heat to study heat and combustion effects on seeds (Franzese and Ghermandi 2012, Ruprecht *et al.* 2013), soils (Hogue and Inglett 2012), or ash nutrients (Qian *et al.* 2009) in the absence of field conditions. Each of these approaches has benefits compared to prescribed fires, but they lose many of the ecological interactions present in field-based fires.

Our objective was to compare time-temperature profiles, maximum temperatures, heat durations, and heat dosages of several experimental approaches—burn box, burn table, and propane prong—to prescribed fires to determine how closely these approaches simulate prescribed fires. We chose to compare prescribed fires and experimental approaches using time-temperature curves, maximum temperature, heat duration, and heat dosage because these parameters are commonly reported in the recent literature and easy to quantify in prescribed fires and controlled experiments. Additionally, temperature and heat duration are used to determine heat dosage, a good predictor of plant mortality (Vermeire and Roth 2011, Strong *et al.* 2013), an important aspect of grassland fire ecology. We used approaches with modified fuels—additional hay or propane—from either the tallgrass or mixed-grass prairie to characterize prescribed fires and experimental approaches.

METHODS

Prescribed Fires

We performed two dormant-season and two growing-season prescribed burns within the tallgrass prairie in North Dakota, USA (46° 31' N, 97° 06' W) and Oklahoma, USA (36° 06' N, 97° 23' W). We conducted one fire for each season and area combination (n = 4). Plant communities were dominated by C_4 grasses, forbs, and shrubs. Average fuel loads in growing-season fires were 5545 kg ha^{-1} and 5036 kg ha^{-1} in dormant-season fires. We ignited prescribed fires using a ring-fire technique incorporating both back and head fires. We distributed two HOBO® U12 Thermocouple Data Loggers (Onset, Cape Cod, Massachusetts, USA) with 24 AWG (American Wire Gauge) K-thermocouples with insulated wire throughout burn units to record temperatures 10 cm above the soil surface. We monitored weather conditions during fires with a Kestrel 4000® device (Loftopia, LLC, Birmingham, Michigan, USA) every 1800 sec (Table 1).

Experimental Approaches

We recorded temperatures during experiments using 24 AWG K-thermocouples with insulated wire and a CR100 data logger

Table 1. Mean temperature, wind speed, and relative humidity during prescribed fires and experimental approaches in Montana, North Dakota, and Oklahoma, USA, in 2012 through 2014.

Weather measurement	Growing season	Dormant season	Burn table	Burn box	Propane prong
Mean temp (°C)	28	14	24	23	6
Wind speed (km h^{-1})	5.0	8.5	9.5	9.7	0.0
Relative humidity (%)	40	41	53	47	95

(Campbell Scientific, Logan, Utah, USA), averaging temperatures over 0.5 sec intervals. We monitored fire weather conditions with a Kestrel 4000 device before every burn when applicable (Table 1).

Burn box. We conducted the burn box approach in eastern Montana, USA, on the Charles M. Russell National Wildlife Refuge (47° 41' N, 107° 10' W) during the growing season. The mixed-grass prairie and sagebrush (*Artemisia* spp. L.) landscape was dominated by native C_3 graminoids and shrubs. We constructed burn boxes around *in situ* vegetation using four 2 m × 2 m aluminum sheets to form a square burn perimeter. We added timothy (*Phleum* spp. L.) hay to adjust all fuel loads to 3000 kg ha^{-1}, typical of the plant community, and ignited fires using a propane torch. We recorded time-temperature profiles using three thermocouples 10 cm above the soil surface during each replicate (n = 5).

Burn table. We grew several native and non-native grass species in 15 cm plastic pots with a substrate mixture of sandy loam soil and commercial sand to conduct the burn table and propane prong experiments. The burn table approach used a metal burn table, elevated off the ground, measuring 1.2 m × 2.4 m with five 16.5 cm diameter circles (Limb *et al.* 2011). Our burn table did not have sides like other fuel beds (Weise *et al.* 2005, Limb *et al.* 2011). We placed five pots below the table so that plant crowns were level with the tabletop. We spread timothy hay at a rate of 3000 kg ha^{-1} on the table and around plant bases with a 10 cm fuel-free border to prevent fuel from falling off and ignited head fires with a drip touch. We recorded time-temperature profiles using three thermocouples 10 cm above the soil surface during each replicate (n = 5).

Propane prong. The third approach utilized a propane prong constructed from 19 mm diameter black pipe, a pressure regulator, a venturi tube for mixing oxygen and fuel, and a standard propane tank. We formed the prong in a U shape with two 30 cm arms with holes every 6 mm (Figure 1). We burned five pots with paired plants for 60 sec between the prongs with a thermocouple 10 cm above the soil surface. We conducted all of our burns inside a closed structure with ventilation.

Figure 1. Images for each of the three experimental approaches conducted in Montana and North Dakota, USA, from 2012 to 2014. The top panel shows the burn box with one missing sheet to show the placement of the added biomass with *in situ* vegetation. The middle panel shows the burn table using plants rooted in pots and added timothy hay. The bottom panel shows the propane prong that was used inside an enclosed structure to burn plants rooted in pots.

Fire Measurements and Statistical Analysis

We averaged temperatures over the thermocouples for each fire to create mean time-temperature curves for each prescribed fire and experimental approach (Figure 2). We identified the mean maximum temperature as the peak from each time-temperature profile. We determined heat duration as the time (sec) above 60 °C and heat dosage in degree-seconds (°C · sec) as the sum of the products of time and temperatures above 60 °C (Russell *et al.* 2013, Strong *et al.* 2013). We compared differences in these three dependent variables across independent fires (two prescribed fires and three experimental approaches) using a univariate generalized linear model with a one-way analysis of variance (Anova) and post-hoc Tukey tests (α = 0.05) in SPSS version 22.0 (IBM, Armonk, New York, USA).

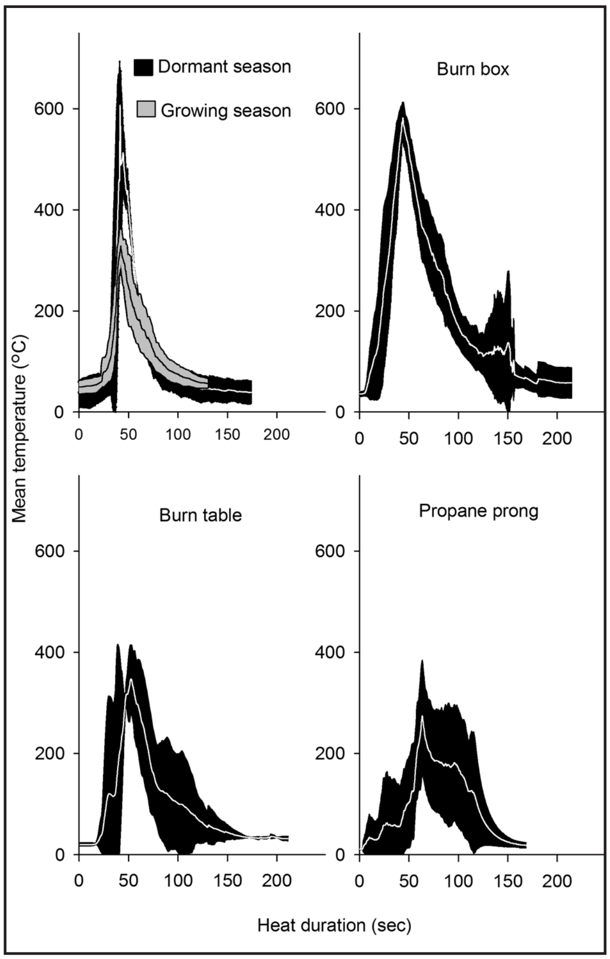

Figure 2. Mean time-temperature profiles for growing-season and dormant-season prescribed fires and burn table, burn box, and propane prong approaches in Montana, North Dakota, and Oklahoma, USA, from 2012 to 2014. The white line represents the mean and shaded areas (black or gray) represent 95 % confidence interval for each curve.

RESULTS

Prescribed, burn table, and burn box fires had similarly shaped time-temperature profiles (Figure 2). Generally, curves increased at a high rate during warming, reached a short peak around the maximum temperature, and gradually decreased during cooling. The propane prong warming and cooling curves were similar to the prescribed fires and other approaches, but the profile plateaued at a sustained elevated temperature instead of peaking.

We found a difference in maximum temperature ($P \leq 0.001$), heat duration ($P \leq 0.001$), and heat dosage ($P \leq 0.001$) between prescribed fires and experimental approaches. Dormant-season and burn box fires averaged maximum temperatures 278 °C hotter than the growing-season, burn table, and propane prong fires. On average, heat durations were 72 sec longer in burn table and burn box fires compared to the prescribed and propane prong fires. Total heat durations were similar between the prescribed and propane prong fires. However, there was no difference ($P > 0.05$) between prescribed and burn box fires (Figure 3).

Heat dosage also varied between fires, like heat duration. High maximum temperatures and longer heat durations led to higher heat dosages in the burn box and burn table approaches. Heat dosages in the burn box were almost two times higher than the prescribed and propane prong fires. Although heat dosages in the burn table approach were almost twice as much as dormant-season fires, there was not a statistically significant difference ($P > 0.05$) between dormant-season and burn ta-

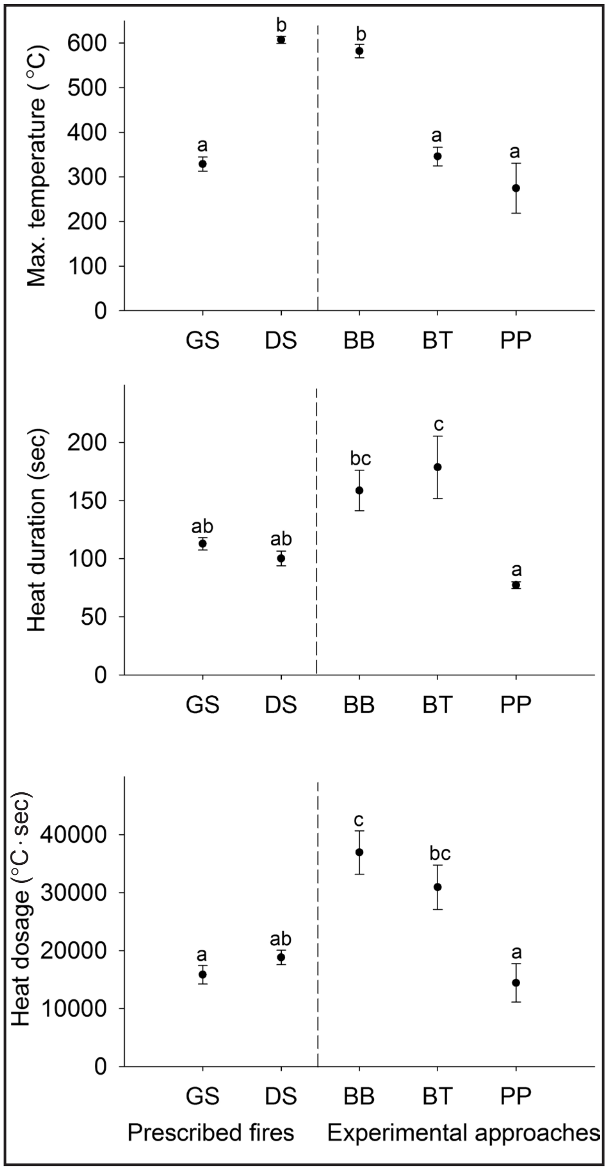

Figure 3. Mean maximum temperature, total heat duration, and heat dosage for growing-season (GS) and dormant-season (DS) prescribed fires and burn box (BB), burn table (BT), and propane prong (PP) approaches in Montana, North Dakota, and Oklahoma, USA, from 2012 to 2014. Error bars are shown for each mean. Different letters correspond to a difference at $\alpha = 0.05$ within each measurement across fires from the post-hoc Tukey test.

ble fires. Heat dosages in the burn table approach were approximately 16 000 °C · sec higher than the growing-season and propane prong fires (Figure 3).

DISCUSSION

There are inherent differences between using prescribed fires and experimental approaches to study fire ecology (Sullivan *et al.* 2013). Experimental approaches can determine effects of temperature (Wright 1971) and different combinations of disturbance and plant age (Limb *et al.* 2011) on individual plant species survival. Generally, experimental approaches are used for finer-scale manipulations to produce more experimental data over a wide range of conditions to better apply fire ecology concepts to larger landscapes. Conversely, most field studies only use burned or nonburned as treatments (Fuhlendorf *et al.* 2011). In our study, the burn table and propane prong provided the closest simulation to prescribed fires, but all approaches could successfully be used to simulate fire. Slight modifications can be made to fuel loads and propane pressure to mimic areas of interest depending on region, study question, and vegetation.

Generally, time-temperature profiles from the prescribed, burn table, and burn box fires were similar to curves determined in other studies with prescribed fires (Engle *et al*. 1989, Archibold *et al.* 1998, Ohrtman *et al.* 2015). These time-temperature curves reached a quick peak and cooled slowly, while the propane prong profile stabilized at hotter temperatures before decreasing. Propane burners produce curves typical of prescribed fires with a quick peak under certain conditions (Wright 1971, Wright *et al.* 1976). However, temperatures measured at the soil surface in other propane burners produced similar results as our propane prong with sustained hotter temperatures (Wright 1971). To create realistic fire curves with the propane prong, fuel adjustments should be made during the burns. We only burned at one rate for a certain time frame as done in other studies (Wright 1971), but it would be better to slightly increase fuel pressure until the target maximum temperature is reached and then slowly decrease fuel pressure to mimic flame fronts and smoldering material. It may also be useful to disconnect the two sides of the prong and move them closer and farther away from the plants to increase or decrease heat exposure.

Maximum temperatures for prescribed fires and experimental approaches were within range of other fires throughout the mixed-grass (Archibold *et al.* 1998, Vermeire and Roth 2011, Strong *et al.* 2013) and tallgrass (Engle 1989, Ohrtman *et al.* 2015) prairie but hotter than maximum temperatures found in the shortgrass prairie (Augustine *et al.* 2014). Maximum temperatures were hotter in dormant-season fires compared to growing-season fires. This temperature trend may be region-dependent for prescribed fires, as growing-season fires can produce hotter (Ansley *et al.* 2006) or similar (Strong *et al.* 2013) maximum temperatures compared to dormant-season fires in other areas. Generally, dormant-season fires have drier fuels, which can produce hotter maximum temperatures (Bragg 1982). Therefore, moisture content and the amount of senesced material can be important factors for explaining differences between various fire characteristics (Brooks *et al.* 2004). Even though burn box and burn table approaches used timothy hay, dormant-season fires utilized a larger proportion of senesced vegetation and produced hotter maximum temperatures.

Because heat can be partially confined in the burn box, the presence of shrubs could account for increased maximum temperature in this approach, as shrubs have longer cooling time-temperature curves due to smoldering coarse, woody fuels (Archibold *et al.* 1998). However, in field-based fires with predominantly smaller shrub species like snowberry (*Symphoricarpos occidentalis* Hook), grassland and shrubland fire temperatures are similar (Bailey and Anderson 1980), so it is unlikely that shrubs caused the temperature increase in the burn box approach. Although high maximum temperatures contribute to plant mortality and can be an important characteristic to determine in fire research, heat duration and heat dosage have been found to be better predictors of plant responses to fire (Strong *et al.* 2013).

Heat durations can be highly variable, even within the same study (Strong *et al.* 2013). Heat durations we observed in our prescribed fires and experimental approaches were similar to some fires (Vermeire and Roth 2011) but lower than other studies (Ohrtman *et al.* 2015) that measured heat duration as time above 60 °C. The variability in heat duration is most likely caused by a combination of additional factors including fuels and weather (Strong *et al.* 2013). In the mixed-grass prairie, heat dosages ranged from around 1000 °C·sec to 26 000 °C·sec (Vermeire and Roth 2011, Strong *et al.* 2013). Heat dosages in our fires never reached the lower end calculated in the above studies. However, dosages in the prescribed and propane prong fires fell within that range. Although calculated slightly differently, heat dosages in the tallgrass prairie were approximately 10 000 °C·sec above heat dosages found in this study (Engle *et al.* 1989).

Heat dosage is an important characteristic in fire ecology because it can explain plant mortality by combining temperature, heat duration, and weather conditions instead of just one of these factors (Augustine *et al*. 2014). Overall, heat dosage is considered a better predictor of plant mortality when assessing plant responses to fire (Vermeire and Roth 2011, Strong *et al.* 2013). The burn table and burn box approaches had higher heat dosages compared to the prescribed fires, so they could cause plant mortality similar to propane burners used in the field to reduce plant survivability (Britton and Wright 1979).

Methods of fuel manipulation for experimental approaches in our study included adding timothy hay or using propane to burn rooted plants. Adding cellulose or biomass creates complete burns compared to patchy burns typically found on prescribed fires (Thaxton and Platt 2006). Small-scale approaches with added fuels burn all available material because they lack natural fire breaks found on larger-scale prescribed fires that create non-burned areas. Complete burning increased maximum temperatures and smoldering, which increased heat duration and heat dosage in the burn table and burn box approaches. The fuel loads were lower in these approaches compared to prescribed fires and still produced higher heat dosages. To account for differences between fuel types, studies using cellulose-based fuels in experimental approaches should consider using reduced fuel loads to create realistic heat dosages. This may involve calibrations to understand the relationship between fuel loads and heat dosage on burn tables and burn boxes compared to prescribed fires.

Generally, dissimilarities between maximum temperatures, heat durations, and heat dosages of prescribed fires can be explained by variable fuel loads, along with plant species composition and weather conditions (Archibold *et al.* 1998). In our study, fire characteristic differences between prescribed fires and experimental approaches were explained by manipulated fuels. Many previous studies fail to include fire characteristics like maximum temperature, heat duration, or heat dosage even though these parameters can improve the overall understanding of ecological impacts and recognize variations between fires (Engle *et al.* 1989). Currently, more research is including these parameters to improve interpretation and application of results (Vermeire and Roth 2011, Russell *et al.* 2013, Augustine *et al.* 2014, Ohrtman *et al.* 2015), but field studies are still limited by constraints like size and replication. We suggest using experimental approaches to increase replication and allow for more manipulation of specific fire characteristics to determine their implications on grassland plant and soil responses to fire.

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