Weather and fuel as modulators of grassland fire behavior in the northern Great Plains

Devan Allen McGranahanA,C, Megan E. ZopfiB, Kathryn A. YurkonisB

A USDA Agricultural Research Service, Livestock and Range Research Laboratory, Miles City, Montana, USA

B Department of Biology, University of North Dakota, Grand Forks, North Dakota, USA

C Corresponding author. Email: [Devan.McGranahan@usda.gov](mailto:Devan.McGranahan@usda.gov)

# Abstract

Fuel and weather interact to affect wildland fire behavior, but little is known about associations between these variables in the northern Great Plains of North America. Few studies consider rate of spread or statistically test the influence of fire environmental variables. We measured fuel load and moisture ahead of prescribed fires in North Dakota, USA, and used a multi-channel thermocouple array to measure rate of spread, soil surface temperature, and flame temperature, which we compared with fire weather data. Aboveground flame temperatures averaged 225C during spring burns in and 250C during fall burns. Surface temperatures averaged just above 100C, although 50% of observations were 60C or less. Fires spread at an average of 2.5 m min. Regression analysis indicated that wind speed drove faster rates of spread while higher fuel loads and lower overall fuelbed moisture produced higher flame temperatures. None of our measurements explained variability in soil surface temperature, likely because ground-level heating remained low. We highlight differential responses among fire behavior metrics to different components of the wildland fire environment. Results help wildland fire managers match burn conditions to desired outcomes, and fire ecologists match measurements to specific ecological responses. We also discuss remaining knowledge gaps in how management and ignition patterns interact to create variability in fire behavior.

**Key words:** Grassland fire ecology and management; Prescribed fire; Rangeland fire management; Robust wildland fire science; Wildland fire science in working landscapes

# Introduction

More than simply the result of combustion of vegetation, fire behavior in wildland environments is multi-faceted, with different components producing different effects on the surrounding environment and organisms within. Most wildland fire scientists describe fire behavior in terms of *rate of spread*—how quickly a flame front moves through a fuelbed—and *intensity*—a suite of measurements of how much energy is released by combustion, often expressed as a rate of energy release over time (McGranahan and Wonkka 2021).

Wildland fire behavior is controlled by interactions between several abiotic and biotic factors, and understanding them is critical to safe and effective wildland fire management (Benson *et al.* 2009). *Abiotic factors* include those determined by the physical environment, such as wind speed and atmospheric moisture content. Wind speed has long been recognized as a primary driver of fire behavior, especially in well-cured grassland fuels (Cheney and Gould 1995; Kidnie and Wotton 2015; Whittaker 1961). Two measures of atmospheric moisture content—relative humidity and vapor pressure deficit—are also associated with fire growth (Sedano and Randerson 2014; Evett *et al.* 2008; Reid *et al.* 2010).

*Biotic factors* relate principally to the amount and nature of plant biomass available for combustion. Overall, energy release rates increase as more fuel is available to burn; the structure and arrangement of vegetation is also important. Greater fuel load attributable to longer time-since-fire increases fire temperature, and spatial variability in fuel load and patchy distribution of fine fuels in turn drive variability in fire behavior (Patten and Cave 1984; Gibson *et al.* 1990; Gomes *et al.* 2020). Furthermore, fine-leaved grasses burn more completely and hotter than an equal mass of forbs (Wragg *et al.* 2018). Finally, fuel moisture content is an especially important driver outside of the highly-cured context of wildfire seasons (Sparling and Smith 1966; Kidnie and Wotton 2015). Together, variability in flammability traits and curing rates among species that comprise grassland fuelbeds contributes to variability in fire behavior (Cruz *et al.* 2015; Kidnie and Wotton 2015; Cardoso *et al.* 2018; McGranahan *et al.* 2016).

How and where within the wildland fire environment fire behavior measurements are made matters a great deal to assessing fire effects. For decades, fire ecologists have measured fire behavior as *flame temperature* via various methods, including arrays of temperature-sensitive paints (e.g., Whittaker 1961; Smith and Sparling 1966; Bailey and Anderson 1980) or by recording air temperature as a flame front passes over a thermocouple connected to a datalogger (e.g., Strong *et al.* 2013; Russell *et al.* 2015).

Despite its popularity among fire ecologists, temperature alone is a poor response variable fraught by several issues in collecting and interpreting thermocouple data (see review by McGranahan 2020). Firstly, a considerable amount of variability in temperature is attributable to sensor placement relative to both the ground and the fire. There is neither a standard for placing thermocouple probes in the wildland fire environment nor consistency in vertical temperature profiles. Most observations of surface fire temperature profiles describe an inverse, linear relationship between height and temperature (Smith and Sparling 1966; Patten and Cave 1984; Archibold *et al.* 2003), although Ramsay and Oxley (1996) found the highest temperatures at the top of a 1 m profile and the lowest temperatures at 30 cm, while Frost and Robertson (1987) and Bailey and Anderson (1980) present evidence that the highest temperatures occur midway up the profile. At least some of this variability might be due to differences in surface vs. flame temperature among head and back fires (Trollope 1978).

Secondly, many factors that contribute to variability in temperatures recorded by thermocouples are attributable to the nature of the sensor rather than the nature of the fire (e.g., Walker and Stocks 1968). Thus, reporting ‘device temperatures’ alone impedes comparisons between studies; Bova and Dickinson (2008) present a standard calibration of thermocouple probes, while McGranahan (2021) simply uses the timestamps of peak heating across an array of several thermocouples to calculate rate of spread. Using rate of spread as the response variable makes moot the third issue with temperature as a fire behavior metric: temperature of the media around a probe is a poor proxy for the thermal experience of an organism. Measures of intensity or energy flux are more biologically relevant (Kremens *et al.* 2012; Smith *et al.* 2016).

In the North American Great Plains, most reports of grassland fire behavior consist of temperatures derived from thermocouples, and there are few data on rate of spread. Soil surface temperatures in South Dakota tallgrass prairie ranged from 200-500C during spring burns, and were greatest under lower fuel loads (Ohrtman *et al.* 2015); fires in Saskatchewan mixed grass prairie exceeded 300C 5-10 cm above the soil surface in spring, summer, and fall (Archibold *et al.* 2003). Mean temperatures in experimental burns in eastern Montana ranged from 172-222C in the summer to 253C in the spring (Strong *et al.* 2013; Russell *et al.* 2015). To our knowledge, no studies on grassland fire in the northern Great Plains region has explicitly tested the effect of fire weather on fire behavior.

Our objectives were to (1) describe the range of variability in three measures of fire behavior—rate of spread, soil surface temperature, and flame temperature 15 cm above soil surface—during prescribed burns in typical fuelbeds of the northern US Great Plains, and (2) explain variability in fire behavior in terms of abiotic and biotic conditions. Our analysis emphasizes the differential effects of environmental variables among the three responses, and the multidimensional relationship among these different measures of grassland fire behavior during prescribed burns conducted at scales consistent with land management in the region.

# Methods

## Study locations

We sampled 25 prescribed fires at two locations in central and southwestern North Dakota, USA (Maps in Supplemental Information Figure 1). At both locations, sampled grasslands are included in a patch-burn grazing study that requires a portion of each experimental unit to be burned each year (Spiess *et al.* 2020). The majority of the burn units were 16 ha, while a small set were 8 ha. Typical ignition patterns consisted of downwind backing fires followed by either ring ignition and primarily head fire spread, when fuels were conducive; when fuels were sparse or higher-moisture, flanking fires and strip ignitions were employed as necessary to ensure fire spread through the entire burn unit.

In central North Dakota, we sampled 15 spring (May) fires at the North Dakota State University Central Grassland Research Extension Center near Streeter, ND (46.718686 N, 99.448521 W). Burned grasslands at this location are divided into two 260 ha blocks with four, 65 ha pastures each in which either an 8- or 16-ha patch is burned each spring. Located in a mixed-grass prairie ecoregion, this location has a rolling topography and receives an average of 468 mm annual precipitation. Vegetation is mixed-grass prairie invaded by introduced, C grasses; stands are dominated by *Pascopyrum smithii*, *Nassella viridula*, *Poa pratensis*, *Bromus inermis*, *Koeleria macrantha*, *Artemisia* spp., *Solidago* spp., and clumps of *Glycyrrhiza lepidota* and *Symphoricarpos occidentalis*.

In southwestern North Dakota, we sampled ten, 16-ha fall (October) fires in two blocks at the North Dakota State University Hettinger Research Extension Center, Hettinger, ND (46.004443 N, 100.646477 W) with mean annual precipitation of 380 mm. Topography is consistently flat. Located in a shortgrass prairie ecoregion, these pastures are dominated by introduced C grasses *Thinopyrum intermedium*, *Bromus inermis*, *Agropyron cristatum*, and *Poa pratensis*, along with the non-native legume *Medicago sativa*.

## Data collection

We measured each fire with a set of 9, 1 m equilateral triangle plots arranged in a nested fashion such that three 10 m triangles, each containing 3, 1m plots, were placed 100 m apart to form a total plot area of 0.433 ha with 27 sample points positioned at the centroid of each burn unit (A detailed schematic of this layout is presented in Supplemental Information Figure 2). This fractal design is modified from the Sierpinksi triangle described by Dorrough *et al.* (2007) and applied to measuring wildland fire spread by McGranahan (2021). Although the logarithmically-scaled nested design was intended for geospatial analysis of point-level data, for our analyses here we calculate averages from the finest (1 m) scale, consistent with the method of locating multiple microplots within larger burned areas to characterize spatial variability within fires (Fernandes *et al.* 2000).

**Fuel data** were collected no more than three hours prior to fire ignition. We clipped and collected all fuels in a 25 × 25 cm quadrat positioned 0.5 m away from each 1 m triangle vertex; the three measurements per plot were averaged prior to analysis. Fuel samples were initially placed in airtight plastic bags to retain moisture, and then weighed, dried to constant mass at 60C for 48 hours, and reweighed. These data were used to calculate percent fuel moisture content (expressed on a dry-weight basis) and fuel load (kg m) for each plot (n = 9 subsamples for each fire).

**Fire behavior data** were recorded as temperature (C) associated with the advancing flame front at each of the 27 points arranged in 9, 1 m triangles at the center of each burn unit. Data were recorded with the open-source FeatherFlame thermocouple datalogger system (McGranahan 2021), logging at 1.5 Hz. Briefly, the FeatherFlame system reads overbraided, ceramic fiber-insulated, 20-gauge K-type thermocouples (Omega, Norwalk, CT) connected to an Arduino-based datalogger assembled from Adafruit Feather breakout boards (M0 Adalogger, datalogging shield, and OLED display; Adafruit Industries, LLC, New York City, NY) and housed inside water-resistant Pelican cases (Pelican Products, Inc, Torrance, California). The low cost of open-source systems make multiple units more affordable than proprietary data loggers with no sacrifice in data quality (McGranahan and Poling 2021).

At each 1-m triangle—the individual observational unit in the nested plot design—we used four thermocouples connected to a single FeatherFlame datalogger. Three thermocouples measured flame temperature 15 cm above the soil surface at each 1 m vertex while a fourth thermocouple recorded soil surface temperature at a representative point within the 1 m array. Beads of the thermocouple probes extended at least 3 cm from the supporting apparatus, to which the insulated lead was attached with wire. The soil thermocouple was placed on mineral ground, perpendicular to the soil surface, below plant litter.

For each fire event, we determined the time and value of the maximum temperature (C) as the flame front encountered each thermocouple. We calculated the maximum flame temperature (C) 15 cm above soil surface for each plot as the mean of the thermocouple readings from its vertices. We calculated the rate of spread (m min) of the flame front as it passed through each plot using the maximum temperature timestamps following equations from Simard *et al.* (1984), which are presented in full in Supplemental Information.

**Fire weather data** were obtained after each fire from records made available by the North Dakota Agriculture Weather Network, the statewide mesonet system with sensor arrays at both experimental stations. We downloaded hourly relative humidity (%), dew point (C), air temperature (C), and average wind speed (m s). From these data we calculated atmospheric vapor pressure (e) and saturation vapor pressure (e) and used these quantities to determine the vapor pressure deficit (VPD = e - e) for the hour in which each fire behavior observation occurred. These data capture hourly trends in weather at the meso-gamma scale (2-20 km; Orlanski 1975), and are reliably connected to our fire behavior measurements via time stamps provided by the dataloggers. The Hettinger mesonet array is 3–8 km from burned pastures, while the Central Grasslands mesonet array is 1–7.5 km from burned pastures. We found a high degree of consistency between these meso-scale data and fire weather records made on the fireline during operational periods, and the open rangeland physiognomy with flat to rolling terrain precludes substantial microsite differences in weather between these records and the conditions at each fire behavior sample point.

## Data analysis

Prior to analysis, we ensured statistical power across 167 observational units by using multiple imputation to interpolate missing datapoints, as missing field data occurred for three rate of spread samples (2% of total), 29 fuel load values (17%), and 46 soil surface temperature values (27%). We used the multiple imputation method in the *mice* package (van Buuren and Groothuis-Oudshoorn 2011) in the R statistical environment (R Core Team 2020) to fill in these missing values. The procedure simulated 50 datasets with different, but reasonable, values for the missing data based on patterns in the existing data. We then scaled all variables to a common range within each imputed dataset, performed regression analysis on each *mice*-generated dataset, and report composite statistical results pooled from the results of the 50 individual regression models.

**Multivariate analysis.—**We first conducted a multivariate analysis to assess composite relationships among the fuel, weather, and fire behavior responses. We used Principal Components Analysis (PCA) fit with the ‘rda’ function in the *vegan* package for R (Oksanen *et al.* 2017). We performed post-hoc group (location) and gradient (fire weather) analysis with the vegan ‘envfit’ function, stratified by year.

**Regression analysis.—**We assessed weather and fuel effects on three fire behavior response variables: Maximum flame temperature (C) 15 cm above the soil surface (mean of three thermocouples), maximum soil surface temperature (C; single thermocouple), and rate of spread (m min) through each 1 m equilateral triangle plot. Because all three response variables were best modeled with a gamma distribution, we fit generalized linear mixed-effect regression models for each response with the ‘glmer’ function from the *lme4* package in R (Bates *et al.* 2015). Fixed effects consisted of weather and fuel variables, as described above. The random-effect term was constructed to account for random variance among locations, spatial non-independence within locations and nested variance within sample plots, and the effect of repeated measurements within each location. Due to concerns about collinearity between relative humidity and vapor pressure deficit because they are derived from the same variables, vapor pressure deficit was excluded from regression analysis for all three response variables.

# Results

Most measures of fuel, fire weather, and fire behavior showed considerable variability within each location, although rates of spread were generally low (Fig. 1). Principal Components Analysis indicated fire behavior patterns were consistent across locations (P = 0.11), although the fall season in Hettinger—our semi-arid location in southwestern North Dakota—tended to have drier air and hotter fires (Fig. 2). Spring fires in the Central Grasslands were conducted under warmer and more evaporative (VPD) conditions than fall fires at Hettinger. The first two axes of the Principal Components Analysis (Fig. 2) explained 86% of overall variance in the fire behavior dataset. The first axis (52% variance explained) was most strongly associated with flame temperature and rate of spread, while the second axis was more strongly associated with soil surface temperature. Dew point was marginally related (p < 0.05) and inversely associated with flame temperatures and rate of spread.

Fires at both locations were characterized by considerable variability among sub-plots. Above the soil surface, half of the fires (13) exceeded 325C, but only four of those fires had >50% of individual sample plots within the burns reach an average of 325C. Sparse fuels meant that fire did not spread to some individual plots in some burns despite strip ignitions. Among plots that burned, fewer than half exceeded 100C at the soil surface (49 of 121 plots). A majority of the fires (18) had at least one plot exceed 100C at the soil surface, seven had over half of the plots exceed 100C at the soil surface, and only one fire had all plots reach this (a spring Central Grasslands fire). Only 10 fires reached or exceeded 325C on the soil surface, with most of these fires reaching this point in only one plot and never in more than half of the plots.

The effects of fuel and fire weather predictor variables varied across the three response variables (Fig. 3). Fires spread faster with higher wind speeds (t = 2.92, P < 0.01), but no other variable had a statistically-significant association with rate of spread (Table 1). Aboveground flame temperatures increased as fuel load increased (t = 2.82, P = 0.01) and decreased as fuel moisture increased (t = -2.16, P = 0.04). No fuel or weather variable included here had statistically-significant associations with soil surface temperature (Table 1).

# Discussion

In our comparison of three measurements of fire behavior—rate of spread and maximum temperature recorded on the soil surface and 15 cm above the soil surface—against fuel and fire weather variables, we found considerable variability in which predictor variables were associated with different measures of fire behavior. These data directly support the safe and effective application of prescribed fire in the region. Some results are straightforward and consistent with decades of fire safety science; e.g., faster rates of fire spread are associated with higher wind speed and lower relative humidity. Other results add nuance to an ecological understanding of how fire behavior relates to fire effects—e.g., factors like fuel load and overall fuelbed moisture were related with flame temperature but not soil surface temperature, which suggests that direct effects on belowground plant tissue and soil biota are not correlated with aboveground heating and fire spread.

To our knowledge, this is the first study from the northern Great Plains to scrutinize the factors that influence fire behavior, and the first to combine reports of fire spread and temperature data from thermocouples. Most published research on fire spread in the Great Plains is derived from computer simulations (McGranahan *et al.* 2013; Yurkonis *et al.* 2019; Overholt *et al.* 2014). The few field studies from the region mostly report temperature data from thermocouples and rarely incorporate fuel and fire weather data into the analysis; when such information is provided, it is typically included in the study description, not as data. Given the high degree of variability in the wildland fire environment, a mechanistic understanding of grassland fire dynamics will require collect fuel, fire weather, and fire behavior data in a spatially and temporally consistent manner to facilitate statistical analyses of their relationships (McGranahan and Wonkka 2018; Hiers *et al.* 2020).

Mean temperatures recorded in this study are consistent with other reports from northern rangelands. In central Alberta grassland, Bailey and Anderson (1980) observed that surface temperatures varied between 110C and 165C for backfires and headfires, respectively, and headfires averaged 200C 15 cm above the ground; temperatures generally tracked with fuel load. Surface fires through jack pine barrens in Ontario had a similar range as ours: 140-545C (Smith and Sparling 1966). In our study, average 15-cm temperatures were 225C during spring burns in central North Dakota and 250C during fall burns in southwestern North Dakota; surface temperatures at both locations generally averaged just above 100C (Fig. 1).

Discrepancies between our data and others reported in the region are consistent with what would be expected when differences in the fire environment are considered. For example, Ohrtman *et al.* (2015) reported a wide range of maximum temperatures at the soil surface—150-500C—that was generally explained by variability in annual productivity and clipping frequency. Our fires were also cooler than those reported by Archibold *et al.* (2003) in Saskatchewan: using the mid-point of observations made at 10 cm and 20 cm as a comparison, spring fires reached 314C and fall fires reached 298C. But Archibold *et al.* (2003) also reported substantially lower fuel moisture in each season and they had approximately three times the fuel load, likely due to an absence of grazing management on the remnant prairie. A previous study reported similar results—temperatures approaching 500C when fuel loads averaged 2.8-4.5 t ha (Archibold *et al.* 1998). With greater variability in fuel load and fuel moisture, we might also expect to see these factors have greater influence on aboveground flame temperatures. For example, in Colorado, Augustine *et al.* (2014) observed a strong linear relationship between fuel load and temperatures ranging from 60-200C, but their fuel load also ranged from 0.2 to 1.2 t ha.

Fires at both of our locations spread much more slowly than most reports from other grasslands, due primarily to high fuelbed moisture content and little opportunity for mitigation by wind or dry air (Fig. 1). Perhaps the most variability in fire spread was reported by Sneeuwjagt and Frandsen (1977) from prescribed grass fires in California and Washington, where rates of spread ranged from 0.2-61 m min. From grassland fires in South Africa and Kansas, USA, Trollope *et al.* (2002) reported average spread rates of 24 and 32 m min, respectively, for head fires and 0.12 and 0.14 m min, respectively, for back fires. In a tallgrass prairie in Texas, Clements *et al.* (2019) recorded fire spreading between 72-150 m min with the wind and 48 m min for flanking fires. Likewise, fires through cured grass fuelbeds in Australia spread much more rapidly than we observed—up to 18-180 m min (Cheney *et al.* 1993; Cheney and Gould 1995; Cruz *et al.* 2015). Through partially-cured stands, though, Cruz *et al.* (2015) found spread rates dropped to 3-44 m min, approaching our location averages of 2.1 and 3.1 m min. Consistent with our finding that only wind speed had a statistically-significant effect on increasing rate of spread (Fig. 3), Cheney *et al.* (1993) found that wind was by far the most important variable to spread rate.

Interestingly, Cheney *et al.* (1993) found that fires spread faster in undisturbed pastures compared to those that had been cut, which they attribute to differences in fuel structure (height, bulk density) rather than fuel load. This might have implications for fire behavior in our region, where invasive species like *Poa pratensis* generally increase aboveground plant biomass but do so by adding thick dense litter at the soil surface, rather than standing dead fuel in the plant canopy (Gasch *et al.* 2020). While difficult to tease apart statistically in the present data, many burn units in our mesic location in central North Dakota were dominated by *P. pratensis* and indeed, that location tended to have higher fuel loads and lower rates of spread (Fig. 1), consistent with simulations of fire spread through those *P. pratensis*-dominated prairies (Yurkonis *et al.* 2019).

Much is made of the difference in fire behavior between head and back fires in the fire ecology literature, and while we expect these differences translate to different fire effects in our system, making distinctions between fire types is difficult in both our data and our management. Trollope (1978) emphasized that while head fires move faster and generally release more energy, back fires effect greater heating at the ground level. One would expect, then, that back fires would have more opportunity to burn down through even thick *P. pratensis* litter to mineral soil. Unfortunately, our results offer little insight into what fuel or weather variables enhance litter combustion, likely because most of our fires never got very hot at the soil surface—50% of our observations were less than 60C, and 60% less than 100C (Fig. 1). Nor can we differentiate the direction of fire spread with the current trigonometry applied to the triangular thermocouple arrays (Simard *et al.* 1984), although it would theoretically be possible to compare spread direction to wind direction if the latter data were available at a fine enough scale.

The functional difference between head and back fires in the fuelbeds reported here is likely moot. Because our fuels were often sparse, sometimes only marginally cured, and prescriptions precluded taking advantage of higher wind or lower relative humidity to mitigate fuel limitations, we often employed substantial interior ignitions using strip, point, flanking, and spiral patterns that sent flame fronts towards our sensors in all possible directions at different times. While Williams *et al.* (2015) did show that different ignition patterns created additional spatial variability in fire behavior, the effect of shorter line ignitions and spot ignitions was to mitigate the high severity of wildfire and long line ignitions in highly-flammable spinifex fuelbeds. In our case, we had to manipulate ignition pattern just to get fire to carry. Our data are certainly useful in describing the variability in fire behavior across these burns, but do not inform the relationship between ignition pattern and fire behavior. Thus, future research on fire behavior in the northern Great Plains should (1) use experimental plots with consistent fuelbeds to explicitly compare head and back fires set via line ignitions, akin to the experimental burning program described by Cruz *et al.* (2015) in Australia, and (2) attempt to at least address severity, if not fire behavior, in wildfire scenarios via remote sensing and/or modelling.

A more detailed analysis of fuelbed effects on fire behavior also ought to separate fuels into live and dead components, and consider the moisture content of each along with fuel load ratios. Explicitly measuring litter moisture might also be valuable, especially when variability in belowground heating is expected to influence first-order fire effects. We report here the overall fuel moisture content of the entire fuelbed, consistent with descriptive, post hoc statistical approaches to describing fire behavior (Bidwell and Engle 1992; Trollope 1978; Trollope and Potgieter 1985; Trollope *et al.* 2002; McGranahan *et al.* 2016). But predictive fire behavior models accommodate inputs for live and dead fuel categories (Scott and Burgan 2005), and Kidnie *et al.* (2015) found that four categories of live, dead, and senescent fuels best represented differences in grassland fuel moisture scenarios. With this in mind, Cruz *et al.* (2015) employed a hybrid approach in which fuel moisture was measured for the various components, from which a weighted average was used as a predictor variable in regression analysis. They subsequently found that overall degree of curing, not simply live fuel moisture, was the most important variable in explaining the dampening effect of fuel moisture on fire behavior.

Often, time and resource constraints preclude the separation of fine plant material by live and dead class, and overall fuelbed moisture content is the best available data for managers. Although parsing live and dead fuel moisture in the present analysis would probably not better explain variability in our dataset, it would likely contribute to better predictions of fire behavior relative to management objectives if information on overall fuelbed moisture content were available prior to ignition. Unfortunately, the standard clipping and drying method is not compatible with providing day-of fuel moisture data, and visual assessments based on color tend to over-predict curedness (Kidnie *et al.* 2015). However, electronic devices can provide accurate and instantaneous measurements of grassland fuel moisture (McGranahan 2019).

Research must also address the influence of atmospheric moisture conditions on prescribed fire behavior. Several broad-scale, post-hoc analyses of wildfire conditions conclude that atmospheric moisture is an important driver of burned area (Sedano and Randerson 2014; Evett *et al.* 2008; Reid *et al.* 2010). But experiments that explicitly test the immediate effect of relative humidity on fire behavior report no appreciable effect on surface fire temperatures or rate of spread (Sparling and Smith 1966; Trollope and Potgieter 1985). It is likely that atmospheric moisture plays a larger role in modulating fuel moisture content prior to combustion than affecting instantaneous fire behavior itself—consider how fire behavior models take fuel moisture as a parameter and not relative humidity, but include relative humidity as an input to determine fuel moisture content (Rothermel 1983; Cruz *et al.* 2016).

The most appropriate measure of atmospheric moisture content might also be unresolved. We focused our analysis here on relative humidity because it is so common in fire behavior models and fire weather forecasts. But vapor pressure deficit has also been identified as an important driver of fire spread and intensity (Gomes *et al.* 2020). In fact, Srock *et al.* (2018) suggest vapor pressure deficit might be a better measure of atmospheric moisture content for fire predictions, but the Hot-Dry-Windy index they developed to incorporate vapor pressure deficit operates at synoptic scales beyond the spatial extent and operational periods of prescribed burns. Given that substantial changes in atmospheric moisture changes in recent decades are expected to strengthen over the 21st century (Seager *et al.* 2015; Ficklin and Novick 2017), understanding how these dynamics affect fire behavior will be an essential component of managing resilient fire regimes.

This study is novel in that it examines the fire environment at a spatial scale consistent with land management in the region using realistic ignition scenarios. To our knowledge, no other study in the northern Great Plains has reported the behavior of fires larger than experimental plots. Integrating research into management almost invariably requires trade-offs; two already discussed above include (1) measuring only the overall moisture content of the entire fuelbed, being precluded from parsing fuel into live, dead, and litter components, and (2) measuring two-dimensional rate of spread of fire fronts within the burn unit without being able to associate them with wind direction. But these are the respective conditions under which prescribed fire managers in the region decide whether to burn, and ensure fire spread objectives are met. Research conducted at the spatial scales at which management occurs helps managers trust the transfer of knowledge from studies to working landscapes (Sayre 2005; Cacciapaglia *et al.* 2012). For example, all of our fire behavior measurements were made more than 50 m from the initial fire line, the distance identified in simulations and used in wildland fire science to allow flame fronts to achieve a quasi steady state in spread rate (Fernandes *et al.* 2000; Sutherland *et al.* 2020), which is obviously precluded in studies that employ small plots.

# Acknowledgements

We appreciate support from the North Dakota State Agricultural Experiment Station, including K. Sedivec at the Central Grasslands REC and C. Schauer and B. Geaumont at the Hettinger REC. We recognize funding from the University of North Dakota Department of Biology, USDA-NIFA Hatch project number ND02393, and USDA-NIFA AFRI award number 2018-67020-27856. We appreciate the technical assistance of several North Dakota State University graduate students and faculty for assistance with prescribed burning. L. LaFond, C. LaFond, and E. Wahl assisted with datalogger assembly. J. Spiess, J. Cutter, M. Lakey, B. Poling, and A. Steele assisted with sensor deployment and data collection. We appreciate the helpful comments contributed by two anonymous reviewers.

The data that support this study will be shared upon reasonable request to the corresponding author.

The authors declare no conflicts of interest.

# References

Archibold O, Nelson L, Ripley E, Delanoy L (1998) Fire temperatures in plant communities of the northern mixed prairie. *Canadian Field-Naturalist* **112**, 234–240.

Archibold O, Ripley E, Delanoy L (2003) Effects of season of burning on the microenvironment of fescue prairie in central Saskatchewan. *The Canadian Field-Naturalist* **117**, 257–266.

Augustine DJ, Derner JD, Smith DP (2014) Characteristics of burns conducted under modified prescriptions to mitigate limited fuels in a semi-arid grassland. *Fire Ecology* **10**, 36–47. doi:[10.4996/fireecology.1002036](https://doi.org/10.4996/fireecology.1002036).

Bailey AW, Anderson ML (1980) Fire temperatures in grass, shrub and aspen forest communities of central Alberta. *Journal of Range Management* **33**, 37–40.

Bates D, Maechler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. *Journal of Statistical Software* **67**, 1–48. doi:[10.18637/jss.v067.i01](https://doi.org/10.18637/jss.v067.i01).

Benson RP, Roads JO, Weise DR (2009) Climatic and weather factors affecting fire occurrence and behavior. ‘Developments in Environmental Science’. (Eds A Bytnerowicz, M Arbaugh, A Riebau, C Andersen) pp. 37–59. (Elsevier)

Bidwell TG, Engle DM (1992) Relationship of fire behavior to tallgrass prairie herbage production. *Journal of Range Management* **45**, 579–584.

Bova AS, Dickinson MB (2008) Beyond ‘fire temperatures’: Calibrating thermocouple probes and modeling their response to surface fires in hardwood fuels. *Canadian Journal of Forest Research* **38**, 1008–1020. doi:[10.1139/X07-204](https://doi.org/10.1139/X07-204).

Cacciapaglia MA, Yung L, Patterson ME (2012) Place mapping and the role of spatial scale in understanding landowner views of fire and fuels management. *Society & Natural Resources* **25**, 453–467.

Cardoso AW, Oliveras I, Abernethy KA, Jeffery KJ, Lehmann D, Edzang Ndong J, McGregor I, Belcher CM, Bond WJ, Malhi YS (2018) Grass species flammability, not biomass, drives changes in fire behavior at tropical forest-savanna transitions. *Frontiers in Forests and Global Change* **1**, 6. doi:[10.3389/ffgc.2018.00006](https://doi.org/10.3389/ffgc.2018.00006).

Cheney N, Gould J (1995) Fire growth in grassland fuels. *International Journal of Wildland Fire* **5**, 237–247.

Cheney N, Gould J, Catchpole W (1993) The influence of fuel, weather and fire shape variables on fire-spread in grasslands. *International Journal of Wildland Fire* **3**, 31–44.

Clements CB, Kochanski AK, Seto D, Davis B, Camacho C, Lareau NP, Contezac J, Restaino J, Heilman WE, Krueger SK, others (2019) The FireFlux II experiment: A model-guided field experiment to improve understanding of fire–atmosphere interactions and fire spread. *International Journal of Wildland Fire* **28**, 308–326.

Cruz MG, Gould JS, Kidnie S, Bessell R, Nichols D, Slijepcevic A (2015) Effects of curing on grassfires: II. Effect of grass senescence on the rate of fire spread. *International Journal of Wildland Fire* **24**, 838–848. doi:[10.1071/WF14146](https://doi.org/10.1071/WF14146).

Cruz MG, Kidnie S, Matthews S, Hurley RJ, Slijepcevic A, Nichols D, Gould JS (2016) Evaluation of the predictive capacity of dead fuel moisture models for Eastern Australia grasslands. *International Journal of Wildland Fire* **25**, 995–1001. doi:[10.1071/WF16036](https://doi.org/10.1071/WF16036).

Dorrough J, Ash J, Bruce S, McIntyre S (2007) From plant neighbourhood to landscape scales: How grazing modifies native and exotic plant species richness in grassland. *Plant Ecology* **191**, 185–198. doi:[10.1007/s11258-006-9236-y](https://doi.org/10.1007/s11258-006-9236-y).

Evett RR, Mohrle CR, Hall BL, Brown TJ, Stephens SL (2008) The effect of monsoonal atmospheric moisture on lightning fire ignitions in southwestern North America. *Agricultural and Forest Meteorology* **148**, 1478–1487. doi:[10.1016/j.agrformet.2008.05.002](https://doi.org/10.1016/j.agrformet.2008.05.002).

Fernandes PM, Catchpole WR, Rego FC (2000) Shrubland fire behaviour modelling with microplot data. *Canadian Journal of Forest Research* **30**, 889–899.

Ficklin DL, Novick KA (2017) Historic and projected changes in vapor pressure deficit suggest a continental‐scale drying of the United States atmosphere. *Journal of Geophysical Research: Atmospheres* **122**, 2061–2079.

Frost PGH, Robertson F (1987) The ecological effects of fire in savannas. ‘Determinants of Tropical Savannas’. (Ed BH Walker) pp. 93–140. (IRL Press: Oxford)

Gasch CK, Toledo D, Kral-O’Brien K, Baldwin C, Bendel C, Fick W, Gerhard L, Harmon J, Hendrickson J, Hovick T (2020) Kentucky bluegrass invaded rangeland: Ecosystem implications and adaptive management approaches. *Rangelands* **42**, 106–116.

Gibson DJ, Hartnett DC, Merrill GL (1990) Fire temperature heterogeneity in contrasting fire prone habitats: Kansas tallgrass prairie and Florida sandhill. *Bulletin of the Torrey Botanical Club* **117**, 349–356.

Gomes L, Miranda HS, Silvério DV, Bustamante MMC (2020) Effects and behaviour of experimental fires in grasslands, savannas, and forests of the Brazilian Cerrado. *Forest Ecology and Management* **458**, 117804. doi:[https://doi.org/10.1016/j.foreco.2019.117804](https://doi.org/https://doi.org/10.1016/j.foreco.2019.117804).

Hiers JK, O’Brien JJ, Varner JM, Butler BW, Dickinson M, Furman J, Gallagher M, Godwin D, Goodrick SL, Hood SM, Hudak A, Kobziar LN, Linn R, Loudermilk EL, McCaffrey S, Robertson K, Rowell EM, Skowronski N, Watts AC, Yedinak KM (2020) Prescribed fire science: The case for a refined research agenda. *Fire Ecology* **16**, 11. doi:[10.1186/s42408-020-0070-8](https://doi.org/10.1186/s42408-020-0070-8).

Kidnie S, Cruz MG, Gould J, Nichols D, Anderson W, Bessell R (2015) Effects of curing on grassfires: I. Fuel dynamics in a senescing grassland. *International Journal of Wildland Fire* **24**, 828. doi:[10.1071/WF14145](https://doi.org/10.1071/WF14145).

Kidnie S, Wotton BM (2015) Characterisation of the fuel and fire environment in southern Ontario’s tallgrass prairie. *International Journal of Wildland Fire* **24**, 1118. doi:[10.1071/WF14214](https://doi.org/10.1071/WF14214).

Kremens RL, Dickinson MB, Bova AS (2012) Radiant flux density, energy density and fuel consumption in mixed-oak forest surface fires. *International Journal of Wildland Fire* **21**, 722. doi:[10.1071/WF10143](https://doi.org/10.1071/WF10143).

McGranahan DA (2019) A device for instantaneously estimating duff moisture content Is also effective for grassland fuels. *Fire* **2**, 12.

McGranahan DA (2021) FeatherFlame: An Arduino-based thermocouple datalogging system to record wildland fire flame temperatures *in agris*. *Rangeland Ecology and Management* **76**, 43–47. doi:[10.1016/j.rama.2021.01.008](https://doi.org/10.1016/j.rama.2021.01.008).

McGranahan DA (2020) An inconvenient truth about temperature–time data from thermocouples. *Plant Ecology* **221**, 1091–1104. doi:[10.1007/s11258-020-01064-7](https://doi.org/10.1007/s11258-020-01064-7).

McGranahan DA, Engle DM, Miller JR, Debinski DM (2013) An invasive grass increases live fuel proportion and reduces fire spread in a simulated grassland. *Ecosystems* **16**, 158–169.

McGranahan DA, Poling BN (2021) A DIY thermocouple datalogger is suitably comparable to a commercial system for wildland fire research. *Fire Technology* **57**, 1077–1093. doi:[10.1007/s10694-020-01032-7](https://doi.org/10.1007/s10694-020-01032-7).

McGranahan DA, Ramaano R, Tedder MJ, Kirkman KP (2016) Variation in grassland fuel curing in South Africa. *Fire Ecology* **12**, 40–52. doi:[10.4996/fireecology.1203040](https://doi.org/10.4996/fireecology.1203040).

McGranahan DA, Wonkka CL (2018) Wildland fire science literacy: Education, creation, and application. *Fire* **1**, 52.

McGranahan DA, Wonkka CL (2021) ‘Ecology of Fire-Dependent Ecosystems: Wildland Fire Science, Policy, and Management.’ (CRC Press: Boca Raton, FL)

Ohrtman MK, Clay SA, Smart AJ (2015) Surface temperatures and durations associated with spring prescribed fires in eastern South Dakota tallgrass prairies. *The American Midland Naturalist* **173**, 88–98.

Oksanen J, Blanchet FG, Friendly M, Kindt R, Legendre P, McGlinn D, Minchin PR, O’Hara RB, Simpson GL, Solymos P, Stevens MHH, Szoecs E, Wagner H (2017) Vegan: Community Ecology Package. <https://CRAN.R-project.org/package=vegan>.

Orlanski I (1975) A rational subdivision of scales for atmospheric processes. *Bulletin of the American Meteorological Society* 527–530.

Overholt KJ, Cabrera J, Kurzawski A, Koopersmith M, Ezekoye OA (2014) Characterization of Fuel Properties and Fire Spread Rates for Little Bluestem Grass. *Fire Technology* **50**, 9–38. doi:[10.1007/s10694-012-0266-9](https://doi.org/10.1007/s10694-012-0266-9).

Patten DT, Cave GH (1984) Fire temperatures and physical characteristics of a controlled burn in the Upper Sonoran Desert. *Journal of Range Management* **37**, 277–280.

Ramsay P, Oxley E (1996) Fire temperatures and postfire plant community dynamics in Ecuadorian grass páramo. *Vegetatio* **124**, 129–144.

R Core Team (2020) ‘R: A language and environment for statistical computing.’ (Vienna, Austria)

Reid AM, Fuhlendorf SD, Weir JR (2010) Weather variables affecting Oklahoma wildfires. *Rangeland Ecology & Management* **63**, 599–603. doi:[10.2111/REM-D-09-00132.1](https://doi.org/10.2111/REM-D-09-00132.1).

Rothermel RC (1983) How to predict the spread and intensity of forest and range fires. United States Department of Agriculture, Forest Service, General Technical Report INT-143. (Ogden (UT)) <http://www.fs.fed.us/rm/pubs_int/int_gtr143.pdf>.

Russell ML, Vermeire LT, Ganguli AC, Hendrickson JR (2015) Season of fire manipulates bud bank dynamics in northern mixed-grass prairie. *Plant Ecology* **216**, 835–846. doi:[10.1007/s11258-015-0471-y](https://doi.org/10.1007/s11258-015-0471-y).

Sayre NF (2005) Ecological and geographical scale: Parallels and potential for integration. *Progress in Human Geography* **29**, 276–290.

Scott JH, Burgan RE (2005) Standard fire behavior fuel models: A comprehensive set for use with Rothermel’s surface fire spread model. United States Department of Agriculture, Forest Service, General Technical Report RMRS-GTR-153. (Fort Collins (CO))

Seager R, Hooks A, Williams AP, Cook B, Nakamura J, Henderson N (2015) Climatology, variability, and trends in the U.S. Vapor pressure deficit, an important fire-related meteorological quantity. *Journal of Applied Meteorology and Climatology* **54**, 1121–1141. doi:[10.1175/JAMC-D-14-0321.1](https://doi.org/10.1175/JAMC-D-14-0321.1).

Sedano F, Randerson JT (2014) Multi-scale influence of vapor pressure deficit on fire ignition and spread in boreal forest ecosystems. *Biogeosciences* **11**, 3739–3755. doi:[10.5194/bg-11-3739-2014](https://doi.org/10.5194/bg-11-3739-2014).

Simard AJ, Eenigenburg JE, Adams KB, Nissen Jr RL, Deacon AG (1984) A general procedure for sampling and analyzing wildland fire spread. *Forest Science* **30**, 51–64.

Smith DW, Sparling JH (1966) The temperatures of surface fires in jack pine barren: I. The variation in temperature with time. *Canadian Journal of Botany* **44**, 1285–1292.

Smith AM, Talhelm AF, Kolden CA, Newingham BA, Adams HD, Cohen JD, Yedinak KM, Kremens RL (2016) The ability of winter grazing to reduce wildfire size and fire-induced plant mortality was not demonstrated: A comment on Davies et al.(2015). *International Journal of Wildland Fire* **25**, 484–488.

Sneeuwjagt RJ, Frandsen WH (1977) Behavior of experimental grass fires vs. predictions based on Rothermel’s fire model. *Canadian Journal of Forest Research* **7**, 357–367.

Sparling JH, Smith DW (1966) The temperatures of surface fires in jack pine barren: II. The effects of vegetation cover, wind speed, and relative humidity on fire temperatures. *Canadian Journal of Botany* **44**, 1293–1298.

Spiess JW, McGranahan DA, Geaumont B, Sedivec K, Lakey M, Berti M, Hovick TJ, Limb RF (2020) Patch-burning buffers forage resources and livestock performance to mitigate drought in the northern Great Plains. *Rangeland Ecology and Management* **73**, 473–481. doi:[10.1016/j.rama.2020.03.003](https://doi.org/10.1016/j.rama.2020.03.003).

Srock AF, Charney JJ, Potter BE, Goodrick SL (2018) The hot-dry-windy index: A new fire weather index. *Atmosphere* **9**, 279. doi:[10.3390/atmos9070279](https://doi.org/10.3390/atmos9070279).

Strong DJ, Ganguli AC, Vermeire LT (2013) Fire effects on basal area, tiller production, and mortality of the C bunchgrass, purple threeawn. *Fire Ecology* **9**, 89–99. doi:[10.4996/fireecology.0903089](https://doi.org/10.4996/fireecology.0903089).

Sutherland D, Sharples JJ, Moinuddin KAM (2020) The effect of ignition protocol on grassfire development. *International Journal of Wildland Fire* **29**, 70–80. doi:[10.1071/WF19046](https://doi.org/10.1071/WF19046).

Trollope WSW (1978) Fire behaviour – A preliminary study. *Proceedings of the Annual Congresses of the Grassland Society of Southern Africa* **13**, 123–128. doi:[10.1080/00725560.1978.9648846](https://doi.org/10.1080/00725560.1978.9648846).

Trollope WSW, Potgieter ALF (1985) Fire behaviour in the Kruger National Park. *Journal of the Grassland Society of Southern Africa* **2**, 17–22. doi:[10.1080/02566702.1985.9648000](https://doi.org/10.1080/02566702.1985.9648000).

Trollope WSW, Trollope LA, Hartnett DC (2002) Fire behaviour a key factor in the fire ecology of African grasslands and savannas. InViegas DX (ed) ‘Proceedings of the IV International Conference on Forest Fire Research’, Rotterdam, The Netherlands. 1–15. (Millpress: Rotterdam, The Netherlands)

van Buuren S, Groothuis-Oudshoorn K (2011) Mice: Multivariate imputation by chained equations in R. *Journal of Statistical Software* **45**, 1–67.

Walker J, Stocks B (1968) Thermocouple errors in forest fire research. *Fire Technology* **4**, 59–62.

Whittaker E (1961) Temperatures in heath fires. *The Journal of Ecology* **49**, 709. doi:[10.2307/2257233](https://doi.org/10.2307/2257233).

Williams PR, Collins EM, Blackman M, Blackman C, McLeod J, Felderhof L, Colless L, Masters K, Coates S, Sturgess A, Martin G (2015) The influence of ignition technique on fire behaviour in spinifex open woodland in semiarid northern Australia. *International Journal of Wildland Fire* **24**, 607–612. doi:[10.1071/WF14177](https://doi.org/10.1071/WF14177).

Wragg PD, Mielke T, Tilman D (2018) Forbs, grasses, and grassland fire behaviour (H Cornelissen, Ed.). *Journal of Ecology* **106**, 1983–2001. doi:[10.1111/1365-2745.12980](https://doi.org/10.1111/1365-2745.12980).

Yurkonis KA, Dillon J, McGranahan DA, Toledo D, Goodwin BJ (2019) Seasonality of prescribed fire weather windows and predicted fire behavior in the northern Great Plains, USA. *Fire Ecology* **15**, 1–15.

Table 1: Results of generalized linear mixed effect regression models testing three measure of fire behavior against potential predictor variables. Statistics reflect pooled results of 50 imputed datasets using the *mice* package in R; see Methods.

|  |  |  |  |
| --- | --- | --- | --- |
| Response | Model term | t *df* | P |
| Rate of spread |  |  |  |
|  | Wind speed | 3.16 *101* | < 0.01 |
|  | Fuel moisture | -1.12 *43* | 0.27 |
|  | Fuel load | 0.95 *46* | 0.35 |
|  | Relative humidity | -0.47 *89* | 0.64 |
| Flame temperature |  |  |  |
|  | Fuel load | 2.82 *54* | 0.01 |
|  | Fuel moisture | -2.16 *41* | 0.04 |
|  | Relative humidity | -1.19 *120* | 0.24 |
|  | Wind speed | 0.02 *132* | 0.99 |
| Soil surface temperature |  |  |  |
|  | Relative humidity | -1.19 *75* | 0.24 |
|  | Fuel load | -0.48 *20* | 0.64 |
|  | Fuel moisture | -0.47 *40* | 0.64 |
|  | Wind speed | 0.06 *50* | 0.95 |

Figure 1: Distribution of weather, fuel, and fire behavior data for 25 fires in southwestern North Dakota (Hettinger, dark maroon) and central North Dakota (Central Grasslands, light blue). Horizontal gray lines denote 25%, 50% (median) and 75% quantiles; triangles are arithmetic means. Means and standard deviation are also reported in Supplemental Information Table 1.

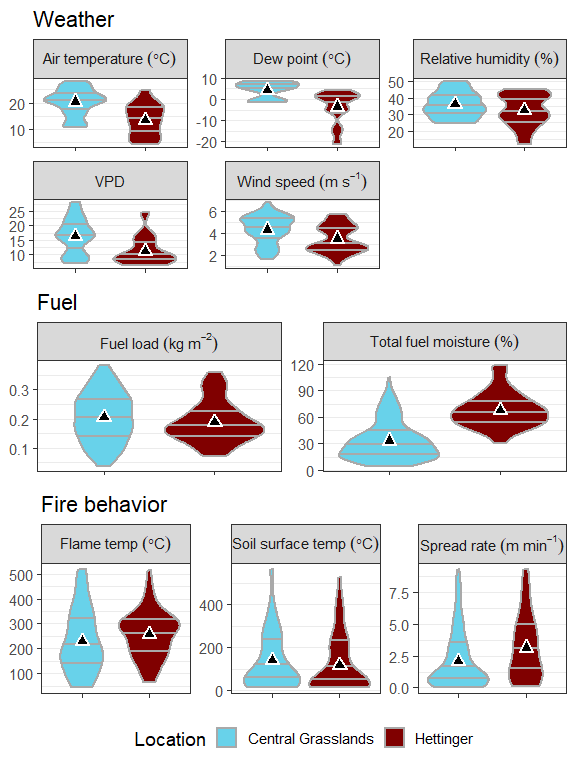


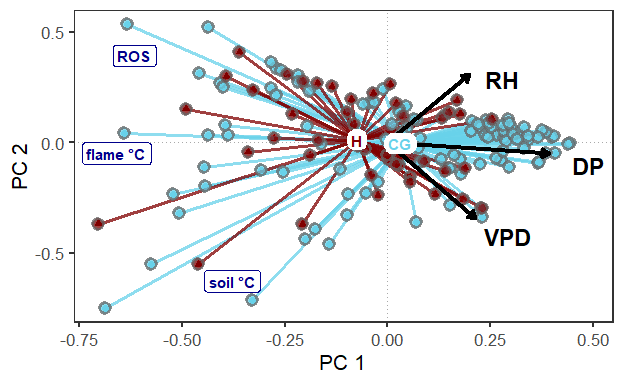
Figure 2: Principal Components Analysis of fire behavior data (response variables in blue; rate of spread (ROS), temperature above surface (flame ºC), and temperature at soil surface (soil ºC) for prescribed burns on rangeland at Hettinger (H), in southwestern North Dakota, and Central Grasslands (CG), in central North Dakota. No difference between locations (P = 0.11). Total variance explained in these two axes = 86%. 

Figure 3: Regression coefficients and 95% confidence intervals for fuel and weather terms from models for maximum temperature at 15 cm above the soil surface (flame), maximum temperature at the soil surface (soil), and rate of spread. 