University of North Dakota
UND Scholarly Commons

Theses and Dissertations

Theses, Dissertations, and Senior Projects

5-2020

Characteristics and Spatial Heterogeneity of Prescribed Fire Behavior in North Dakota Grasslands

Megan Elizabeth Zopfi

How does access to this work benefit you? Let us know!

Follow this and additional works at: https://commons.und.edu/theses

Part of the Biology Commons, and the Ecology and Evolutionary Biology Commons

Recommended Citation

Zopfi, Megan Elizabeth, "Characteristics and Spatial Heterogeneity of Prescribed Fire Behavior in North Dakota Grasslands" (2020). *Theses and Dissertations*. 3134.
https://commons.und.edu/theses/3134

This Thesis is brought to you for free and open access by the Theses, Dissertations, and Senior Projects at UND Scholarly Commons. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of UND Scholarly Commons. For more information, please contact und.commons@library.und.edu.

CHARACTERISTICS AND SPATIAL HETEROGENEITY OF PRESCRIBED FIRE BEHAVIOR IN NORTH DAKOTA GRASSLANDS

by

Megan Elizabeth Zopfi

Bachelor of Science, University of Wisconsin River Falls, 2012

A Thesis
Submitted to the Graduate Faculty
of the
University of North Dakota
in partial fulfillment of the requirements

for the degree of
Master of Science

Grand Forks, North Dakota
May
2020

Copyright 2020 Megan Zopfi

DocuSign Envelope ID: 59ABE95C-91CD-4C06-A864-744377120D7C

This thesis, submitted by Megan Zopfi in partial fulfillment of the requirements for the Degree of Master of Science in Biology from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

DocuSigned by:
Kathryn Yurkonis
2651883DDE5C4F7...
Dr. Kathryn Yurkonis

DocuSigned by:
31E20C42188D45B...
Dr. Devan McGranahan

DocuSigned by:
85C1B9E6E2294D6...
Dr. Brian Darby

Name of Committee Member 3

Name of Committee Member 4

Name of Committee Member 5

This thesis is being submitted by the appointed advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

DocuSigned by:
Chris Nelson
13D0157109424B1...
Chris Nelson
Dean of the School of Graduate Studies

5/4/2020
Date

PERMISSION

Title	Characteristics and spatial heterogeneity of prescribed fire behavior in North Dakota grasslands
Department	Biology
Degree	Master of Science

In presenting this thesis in partial fulfillment of the requirements for a graduate degree from the University of North Dakota, I agree that the library of this University shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by the professor who supervised my thesis work or, in her absence, by the Chairperson of the department or the dean of the School of Graduate Studies. It is understood that any copying or publication or other use of this thesis or part thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of North Dakota in any scholarly use which may be made of any material in my thesis.

Megan E. Zopfi

May 06, 2020

TABLE OF CONTENTS

EFFECTS OF FUELS AND WEATHER ON FIRE BEHAVIOR IN NORTH DAKOTA GRASSLANDS

SPATIAL HETEROGENEITY OF FUELS AND FIRE BEHAVIOR IN NORTH DAKOTA GRASSLANDS

LIST OF FIGURES

INTRODUCTION

EFFECTS OF FUELS AND WEATHER ON FIRE BEHAVIOR IN NORTH DAKOTA GRASSLANDS

SPATIAL HETEROGENEITY OF FUELS AND FIRE BEHAVIOR IN NORTH DAKOTA GRASSLANDS

LIST OF TABLES

EFFECTS OF FUELS AND WEATHER ON FIRE BEHAVIOR IN NORTH DAKOTA GRASSLANDS

SPATIAL HETEROGENEITY OF FUELS AND FIRE BEHAVIOR IN NORTH DAKOTA GRASSLANDS

ACKNOWLEDGMENTS

First and foremost, I would like to thank my advisor Dr. Kathryn Yurkonis. Thank you for being approachable, knowledgeable, and an inspiring mentor. Thank you to Dr. Devan McGranahan, who pushed my boundaries and understanding of fire behavior and international use. And to Dr. Brian Darby, for our regular conversations to improve my understanding of statistical modeling. Financial support was made available by an UND Biology Department APSAC award to Megan Zopfi. Research Committee funds were awarded to Dr. Kathryn Yurkonis and Dr. Brian Darby.

Many thanks to the staff and facilities of the field stations, the NDSU Wildland Fire Crew for the prescribed fire operations at CGREC and HREC, Badger Creek Wildfire and Prairie Restorations, Inc for prescribed fire operations at Oakville. A special thank you to Micayla Lakey, Jonathon Spiess, Jasmine Cutter, and Agnes Steele, who generously assisted with fuels data collection and passive fire behavior sensor deployment.

A special thanks for everyone associated with the Grassland Ecology Lab. Data wrangling was made possible with the aid of Agnes Steele, Madison Conners, and Jaylin Solberg. To Lynda and Chris LaFond, who provided their programming and electrical insight during troubleshooting of the thermocouples.

I would like to thank Evan Wahl: for his patience while I completed this degree, who taught me how to solder during the datalogger construction phase, for building and troubleshooting his fair share of dataloggers, and for being my residual sounding board.

And to my family, who supported my drive for higher education.

ABSTRACT

Fire is a critical physical and chemical process required to sustain many grassland ecosystems. In North America, observations of grassland fire behavior in warm-season, southern grasslands are commonly used in fire behavior modeling efforts across the Great Plains. However, grasslands of the northern Great Plains contain a greater component of cool-season vegetation that may generate different fire behavior. To further our understanding of prescribed fire behavior in North Dakota grasslands, we quantified fuel, weather, and fire behavior characteristics associated with 27 prescribed fires conducted across three sites in North Dakota. We sampled 27 points on each fire arranged into a Sierpinski triangle sampling scheme with three fractally nested spatial scales. Field station are climatologically and vegetatively different sites, yet fuel and weather characteristics associated with the fires were similar. Ultimately, fire behavior was similar between the stations having burned under similar fuel bed properties and weather conditions. Fire behavior averaged 227.26 ± 94.74°C (maximum temperature), 0.4 ± 0.3 m (flame height), 4.47 ± 3.82 m/min (0.07 ± 0.064 m/s; rate of spread). Maximum temperature and flame height were best explained by fuel moisture, relative humidity, and quantity of the last rainfall event. Rate of spread was best explained by dew point, wind speed, and quantity of last rainfall. However, increased fuel moisture and relative humidity suppressed fire behavior. To quantify spatial heterogeneity, we assessed fuel bed properties (fuel load, soil and fuel moisture) prior to ignition and the resulting fire behavior (maximum temperature, flame height, and rate of fire spread) on 26 prescribed fires. We used a hierarchical Restricted Maximum Likelihood (REML) variance component analysis with the full 27-point dataset to assess how each sample scale (100 m, 10 m, 1 m) contributed to the variance in the fuel and fire behavior responses. Fuel loads (LAI) were most variable at higher scales (100 m, 10 m) but most similar at the 1 m scale. Fuel moisture contrasts fuel load in that it was the most variable at 1 m but similar at 100 m. Soil moisture variance was not dependent on the sample scale. Assessing relationships between fuel explanatory and fire response variables, we found similar effects of heterogeneity in fuel load and fuel moisture on maximum temperature and flame height. Maximum temperature and flame height exhibit the most variation when fuel load is most consistent and when fuel moisture variance is high. Rate of spread has a limited dataset and did not relate to the variation in fuel load and fuel moisture. Understanding the spatial variability within the fuel bed and its contribution to fire behavior will aid fire practitioners will better guide future planning efforts and provide a greater understanding of ecological fire effects.

INTRODUCTION

The Great Plains within central North America consist of a diverse collection of plant community types that span precipitation gradients across the region. Notably, the northern Great Plains is comprised of more xeric mixed grass prairie to the west and more mesic tallgrass prairie to the east (Axelrod 1985, Oesterheld et al. 1999, Anderson 2006). In North Dakota alone, mixed-grass prairie historically dominated the landscape at 13,900,000 hectares and tallgrass prairie once occupied an estimated 1,200,000 hectares. Acreage of both habitat types has declined due to land conversion. As of 1994, North Dakota held 3,900,000 hectares of mixed grass prairie and a mere 1200 hectares of tallgrass prairie (Samson and Knopf 1994). Substantially less acreage remains of both grassland types today and restoration and management activities are necessary for their continued existence (Howe 1994, Gibson 2009).

As a disturbance-dependent ecosystem, grasslands such as those in North Dakota rely on periodic episodes of disturbance, such as grazing and fire, to promote temporal and spatial heterogeneity (Sousa 1984). An ecological disturbance is a discrete event that disrupts population structure, community, or ecosystem and affects resources (Pickett and White 1985). Disturbance affects the physical environment and essential ecosystem processes such as primary and secondary production, biomass accumulation, and nutrient cycling (Sousa 1984). Disturbances are usually characterized by their frequency, magnitude, and spatial and temporal extent (Pickett and White 1985).

Fires are fundamentally a product of the fuels, weather, and ignition sources in a region and fire disturbances are typically described by what is known as a fire regime. Fire regimes describe the pattern, historical frequency, intensity, and severity of fires for any given area

(Whitlock et al. 2010, Bowman et al. 2011). Climate broadly determines when during the year that fires can successfully propagate. These so-called fire seasons are defined as periods where fires normally occur for any given ecosystem. Fire seasons typically encompass climatic periods dominated by drier air masses, with less frequent rainfall, lower humidity, and higher solar radiation and temperatures (Pyne 1984, Platt et al. 2015). The regional climate has a strong effect on a fire regime as it dictates temporal patterns of fuel moisture and potential for ignition (Whelen 1995, Morgan et al. 2001, Taylor and Skinner 2003, Power et al. 2008, Pausas and Keeley 2014). In the northern Great Plains, fire seasons are bimodal, peaking in the spring and fall and coinciding with the cycle of seasonal plant growth and senescence (Yurkonis et al. 2019).

This climate-fire relationship was an instrumental force shaping the development of the Great Plains (Gibson 2009, Bowman et al. 2011). Tectonic uplift of the Rocky Mountains to the west during the Laramide orogeny in the Upper Cretaceous period and Mesozoic era (80-55 Mya.) (McMillian et al., 2006; Copeland et al., 2017) created a barricade to prevent cross continental movement of humid oceanic air masses (Anderson 1990). Increased aridity and periodic drought throughout central North America in the Miocene-Pliocene era (7-5 Mya) created a favorable environment for fire-adapted grasses and herbaceous forbs (Axelrod 1985, Edwards et al. 2010). The grasslands we know today evolved during the Holocene (Baker et al. 2000, Cordova et al. 2011). Lightening events served as the primary ignition source for naturally occurring fires prior to the earliest hominid use of fire circa 1.7 to 0.4 Mya. in the lower and middle Pleistocene (James et al. 1989, Coughlan and Petty 2012). Over the last thousand years, indigenous peoples used fire to manipulate the landscape for many services (Pyne 1984) including to affect the seasonal bison migration to ensure successful hunts (Roos et al. 2018).

More recently, early European immigrants implemented pre-industrial, agropastoral practices and used fire for landscape reclamation, to improve forage for domestic livestock and game, to clear land for agriculture, and for pest management (Coughlan and Petty 2012). Sedimentary charcoal records dating to A.D. 1600 indicate that grassland fires peaked (A.D. 1700-1740, A.D. 1850-1900) immediately succeeding waves of European settlement through the Dakotas and Montana (Umbanhowar 1996). Although lighting strike fires still occur (Bragg 1982, Higgins 1984), anthropogenic fire use declined substantially with the industrialization of agriculture (Bowman et al. 2009). Mechanized machinery, herbicides, and pesticides all but terminated the use of broadcast fire on the landscape to the point it became locally regulated (Pyne 1984). Today, socio-economic interests and policy drive landscape management fire use (Pausas and Keeley 2014, Chiodi et al. 2019).

The rapid decline of fire on the landscape over the last century has put regional grasslands at risk for loss of diversity and invasion by non-native and woody plant species (Knapp and Seastedt 1986, Gibson and Hulbert 1987, Gibson 2009, Bowman et al. 2011). As the most successful land management strategies are those that attempt to mimic natural disturbances for which a community is adapted (Hawbaker et al. 2013, Limb et al. 2018), researchers have put substantial effort into characterizing the historical fire regime of the region and making recommendations for future fire management. To promote species diversity and reduce woody encroachment, proposed fire frequencies for mixed grass and tallgrass prairies vary from two to 10 years (Brown and Smith 2000). This recommendation is based on long-term fire frequency research from the central Great Plains who found that maximal plant species diversity and richness occurs with fire regimes in this window. These metrics of community structure decline when fires are more frequent or more infrequent (Whelen 1995, Towne and Kemp 2008, Gross and Romo 2010). Additionally, this regime reflects the rates of fuel accumulation in that Daubenmire (1968) noted biomass could accumulate to pre-fire levels in as little as 3 to 5 years (Pyne 1984, Zedler 2007).

Ecological managers in the Great Plains use objective based, or prescribed, fires to meet grassland management goals, such as reducing accumulated litter and reducing woody species encroachment. Managers have successfully used prescribed fire to enhance above- and below-ground productivity, suppress woody species, and increase plant, avian, and invertebrate species richness and diversity throughout the Great Plains (Coppedge et al. 2008, Engle et al. 2008, Towne and Kemp 2008, Grant et al. 2010, Limb et al. 2018). Although managers are good at articulating objectives related to plant management associated with fires, the desired plant-based outcomes are not always met (Howe 1995, D'Antonio 2000, Emery and Gross 2005). This may be related to a lack of specificity when it comes to planning fires and fire behavior. Modern grassland fire management often involves applying fires based on a predetermined rotational schedule, weather conditions with regard for human safety and infrastructure. As in other ecosystems (Loudermilk et al. 2012, Wiggers et al. 2013), grassland fires can vary in their behavior and intensity and this variation is not often recognized within the efforts to plan and implement prescribed fires. More intense fires with hotter temperatures could more readily reduce the litter layer and woody species. In contrast, less intense fires with cooler temperatures may only do a cursory job of removing accumulated litter and may not provide the heat shock necessary to affect plant species composition and abundance (Whelen 1995, Twidwell et al. 2013, Ratajczak et al. 2014). The binary mentality of applying a fire or not without regard to fire intensity misses a critical opportunity to understand how varying fire behavior and intensity can be used to more effectively reach grassland management objectives.

Nested within the fire regime, a fire event links weather, fuel, and topography at seasonal and annual temporal scales (Whitlock et al. 2010). It is at this scale that fire behavior and its resulting effects are traditionally quantified. Prescribed fires are often viewed as an overarching, singular ecological disturbance, but, chemically, a fire event is a series of repetitious ignitions that interact with properties of the fuel bed (Rothermel 1972). At the finest spatial scale, a flame is a product of heat applied to fuel in the presence of oxygen (Figure 1). Without any one of these components, the fire will extinguish (Pyne 1984, Whitlock et al. 2010, Keane 2015).

To strengthen the discipline of fire ecology, we must determine to what extent weather and fuel conditions at the time of ignition affect fire behavior and how fire behavior affects the local plant community (Morgan et al. 2001, Batllori et al. 2015). Together these factors affect ignition probability and fire behavior such as fire intensity (Byram 1959) and rate of spread (Rothermel 1972). Defined as how a fire will react to the influences of topography, fuel, and weather (NWCG), fire behavior refers to the way fuels ignite, flames develop, and fire spreads (Figure 1). Behavior is probabilistic, irregular, and highly variable (Pyne 1984).

Fire behavior is commonly quantified by its surface temperature, heating duration, flame length, fireline intensity, and rate of spread (m/s) (Figure 2a, b). Byram (1959) introduced a mathematical model to quantify fireline intensity: the energy output released from the flame front per unit time per unit length of the fire front (kW/m or Btu/sec/ft). This model ($I = H \times w \times r$) implies fireline intensity is a numerical function of the heat combustion of fuels consumed subject to fuel moisture conditions (H, kJ/kg), the quantity of fuel consumed per unit area (w, kg/m2), and the linear advance of the fire front (r, m/s) (Byram 1959, Alexander 1982).

Recognizing the critical application of rate of fire spread to the fireline intensity model, Rothermel (1972) built upon previous models to develop a mathematical model to predict the forward rate of fire advancement. Designed for surface fires, this model assumed fireline independence, uniform fuel particle properties and arrangement. The model was accompanied by 11 generic fuel models to predict fire spread and intensity under severe climatic periods at the peak of fire season. The widespread use of the Rothermel fire spread model in variable fuel types and weather conditions has contributed to the development of 40 additional fuel models (Scott and Burgan 2005, Kidnie 2009). Mathematical models such as these listed above allow practitioners to better predict fire behavior under specific fuel bed and atmospheric properties. With the number of potential explanatory variables, quantifying differences in behavior among fires requires multivariate approaches.

Topography works in conjunction with weather and fuel variables to affect fire behavior. Fires burning upslope will exhibit a tilted flame front. This angle enhances convective and radiant energy to preheat the fuels prior to the arrival of the flame front and results in a higher rate of fire spread (Pyne 1984). The duration and level of solar radiation received through aspect affects surface fuel temperatures and the drying of fuels via air temperature and relative humidity (Taylor and Skinner 2003, Hawbaker et al. 2013). In areas of less severe topographic relief, such as the northern Great Plains, topography indirectly generates conditions for heterogeneous fire behavior. Topographic features such as elevation, slope, and aspect produce microclimates on a landscape, and affect fuel moisture, relative humidity, and different interactions with wind, especially near the ground surface (Whelen 1995). Elevation and aspect can affect the spatial distribution and occurrence of plant phenology, fuel moisture, and continuity (Cheney and Gould 1997, Rollins et al. 2004, Cruz et al. 2015).

Of upmost importance when characterizing fire behavior is to consider fuels, as fuels fundamentally govern the outcome of the ignition, combustion, and propagation of a fire (Matthews 2014, Cruz et al. 2015). Fuels are comprised of living and senesced plant material that occur above the mineral soil (A horizon) surface (Keane 2016) and in grasslands are typically vertically stratified into a ground and surface layer. Ground fuels consist of all amorphous organic matter (O horizon) above mineral soil and include duff, rooted living, and partially decomposed plant material. Surface fuels contain all standing live and dead biomass up to 2 meters above the ground surface.

When considering fuels, the amount of moisture within the material strongly affects whether a fire can successfully propagate. Live moisture content at full turgor can exceed 300% of the oven-dry weight, whereas moisture content of dead fuels can fall below 10%. Senesced fuels compose a proportion of the total fuel load in grassland systems. Quantified by the degree of curing, senesced fuels passively exchange moisture with the atmosphere via evaporation, whereas active atmospheric and ecophysiological processes govern the moisture content of live material (Viney 1991, Matthews 2014, Cruz et al. 2015). In order to ignite and combust either fuel type, the water molecules need to be removed to a certain point either through atmospheric drying or via direct heating. Not surprisingly, wetter fuels require a larger heat sink at the expense of the heat source to evaporate this moisture prior to combustion (Keane 2015, Cawson and Duff 2019). As a result, fires ignited during wetter fuel conditions would presumably be cooler and have a lower rate of spread and intensity relative to similar fires conducted under drier fuel conditions (Morvan et al. 2013, Cruz et al. 2016). When planning for a fire, we can assess fuel moisture and its potential effect on fire behavior through intensive direct measurements or indirectly by measuring relative humidity, to some extent air temperature, wind (which affects drying), days since last rain event, and soil moisture. Relative humidity and air temperature will interact to affect fuel moisture (Morvan et al. 2013).

Additionally, the volume (fuel load; typically, dry mass of fuel per unit area in kg/m^2), density, and distribution of fuels affects the extent to which fires propagate across the landscape and fire intensity (Scott and Burgan 2005). Engle et al. (1989) studied the effects of grassland fuel loads on fire behavior and concluded higher fuel loads produced hotter fires of a longer duration, resulting in higher fireline intensity and a moderately increased forward rate of spread. The fuel load is determined by the plant species on site and the site disturbance history (Morgan et al. 2001). Sites with a more recent disturbance history, and thus a lower fuel load, would likely have a lower rate of spread and be cooler. The size and shape of a fuel particle can also affect the rate of spread (Scott and Burgan 2005, Kidnie and Wotton 2015). The high surface-to-volume ratio architecture of grass and herbaceous vegetation promotes rapid desiccation and amplifies the probability of ignition in favorable conditions. Fine fuels such as grasses require small energy inputs for ignition, thus readily allowing for ignition and propagation (Umbanhowar 2004, Zedler 2007). Fires should spread more rapidly and with higher intensity through continuous cured fuels such as fine or coarse grasses (Rothermel 1972, Anderson 1982). The fuel arrangement, or vertical distribution and horizontal continuity of a fuel bed, can also affect the rate of combustion (Scott and Burgan 2005). As the quantity of air available in the fuel bed increases, ignition and therefore combustion become more efficient. When fuels are sparse or compacted, burning efficacy is low resulting in a lower spread rate and potential extinction.

Although fuel characteristics determine a fire, we commonly use atmospheric proxies for anticipating fire behavior. Fire behavior is affected by local site conditions, the quantity of available fuel, and weather conditions at the time of ignition and during the fire event (Thaxton and Platt 2006, Gagnon et al. 2012). Relevant weather variables include relative humidity, air temperature, wind speed, and wind direction (Figure 2). Wind speed affects and available oxygen for combustion. At low wind speeds, less oxygen is available for combustion. The fire will be less intense as it is unable to pre-heat and ignite fuel in advance of the fire front (Whelen 1995).

Because fire behavior is the response to the topography, fuel, and weather conditions at any point on a site, it can potentially be quite variable (Iverson et al. 2004, Rollins et al. 2004) and it is important to understand this variation in order to further our understanding of fire effects (Loudermilk et al. 2009, Keane 2016, Vakili et al. 2016). Fuel-fire behavior models typically integrate fuel parameters over large scales and are really developed for risk assessment applications and fire suppression. As a result, the resulting models produce simplified fuel descriptions and assume fine-scale complexity is inconsequential to fire behavior (Vakili et al. 2016), which may make them less effective for use in management applications. However, this might not be representative as fuels are likely spatially autocorrelated over sub-meter and meter scales (Kalabokidis and Omi 1992). Effective fire and land management requires recognition of the dynamic nature of fuel ecology and its effect on fire behavior (Loudermilk et al. 2009, Duff et al. 2017). Additional research is required to determine to what extent fire behavior mimics fuel heterogeneity (Miller and Urban 2000). Variation in the intensity of a fire across a site can affect the composition and structure of the plant community and the organisms that occupy it as it regrows (Gibson et al. 1990, Whelen 1995, Vakili et al. 2016). This within site variation in fire behavior (Iverson et al. 2004) has been implicated in helping to maintain high plant species richness in fire-managed grasslands and pine savannas (Loudermilk et al. 2009, Mitchell et al. 2009). The best example of this effect is with the interaction of fire and grazed sites (Fuhlendorf et al. 2006, Kerby et al. 2007, Fuhlendorf et al. 2009). This is important to consider when using prescribed fire, as natural disturbances are rarely homogeneous (Mitchell et al. 2009).

Fire behavior can be as much of a product of fuels managers operating on a site, as it is a result of the site abiotic and biotic conditions at the time of ignition. Consideration of weather and ecological conditions combined with training and past experiences influence where, when, and how ignition operations occur. Fuels managers of the northern plains show preference to conduct prescribed fires in the spring when fire weather conditions correspond with dormant or cured fuels (Bragg 1982, Ewing and Engle 1988, LePage et al. 2010). However, many managers are restricted by policy, previous experience, or resource availability to a specific burn season (Yoder et al. 2004, Weir 2011, Schultz et al. 2019). Contributing to the variability of grassland fire behavior, fuels managers attempt prescribed fires under marginal fire weather conditions (Weir 2011, Morvan et al. 2013). Marginal conditions produce diminished fire behavior such as poor fire spread and lower fire temperatures, resulting in reduced effectiveness. If adequate fire weather days are not available, prescribed fires may be postponed until the following year allowing for further accumulation of fuels. Multiyear accumulation of fuel can become compacted and retain moisture, therefore unable to carry fire and requiring several fires to remove standing litter (Zedler 2007). Fire growth can be manipulated through various ignition techniques and fireline shapes. The geometrical shape and width of the flame front directly affects fire line intensity. For example, Cheney and Gould (1997) found grid ignitions produced low fireline intensity during prescribed fire operations in Australian grasslands.

To quantify fuels and their associated fire behavior, we sampled 27 prescribed fires from three university field stations across North Dakota, USA from 2017 to 2019. These field stations, located in northeastern (Oakville Prairie), central (Central Grasslands Research Extension

Center), and southwestern North Dakota (Hettinger Research Extension Center), span a gradient of precipitation and vegetation composition. We sampled 27 points on each fire following Ryan (1981) and Finney and Martin (1992) with a nested Sierpinski Triangle fractal sampling scheme (Figure 3). The fractal spatial design enabled us to capture fire behavior at the fire event, 100 m, 10 m, and 1 m scales. Fuel conditions were documented immediately prior to the fire event and weather data was downloaded from local climate stations (North Dakota Agricultural Weather Network). Through this work, we aimed to characterize fire behavior and identify best explanatory fuel and weather variables for prescribed fires in grassland ecosystems of North Dakota. I anticipate fire behavior will be different among field stations due to variable fuel loads and continuity. I expect stations with higher fuel loads will yield higher temperatures and faster rates of fire spread. We will also identify the fine-scale (sub-meter) spatial heterogeneity of fire behavior within individual fire events. I hypothesize the spatial variation will be determined by plant density and fuel moisture.

Literature Citations

Alexander, M.E. 1982. Calculating and interpreting forest fire intensities. Canadian Journal of Botany **60**.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. General Technical Report INT-122. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Anderson, R.C. 1990. The historic role of fire in the North American grassland. Fire in tallgrass prairie ecosystems *in* L. Wallace and S. Collins, editors. Pages 8-18. University of Oklahoma Press, Norman, OK.

Anderson, R.C. 2006. Evolution and origin of the Central Grassland of North America: climate, fire, and mammalian grazers. Journal of the Torrey Botanical Society **133**:626-647.

Axelrod, D.I. 1985. Rise of the Grassland Biome, Central North America. Botanical Review **51**:163-201.

Baker, R.G., G.G. Fredlund, R.D. Mandel, and E.A.B. III. 2000. Holocene environments of the central Great Plains: multi-proxy evidence from alluvial sequences, southeastern Nebraska. Quaternary International **67**:75-88.

Batllori, E., D.D. Ackerly, and M.A. Moritz. 2015. A minimal model of fire-vegetation feedbacks and disturbance stochasticity generates alternative stable states in grassland-shrubland-woodland systems. Environmental Research Letters **10**.

Bowman, D.M., J.K. Balch, P. Artaxo, W.J. Bond, J.M. Carlson, M.A. Cochrane, C.M. D'Antonio, R.S. DeFries, J.C. Doyle, S.p. Harrison, F.H. Johnston, J.E. Keeley, M.A.

Krawchuk, C.I. Roos, A.C. Scott, T.W. Swetnam, G.R.v.d. Werf, and S.J. Pyne. 2009. Fire in the Earth System. Science **324**:481-484.

Bowman, D.M.J.S., J. Balch, P. Artaxo, W.J. Bond, M.A. Cochrane, C.M. D'Antonio, R. DeFries, F.H. Johnston, J.E. Keeley, M.A. Krawchuk, C.A. Kull, M. Mack, M.A. Moritz, S. Pyne, C.I. Roos, A.C. Scott, N.S. Sodhi, and T.W. Swetnam. 2011. The human dimension of fire regimes on Earth. Journal of Biogeography **38**:2223-2236.

Bragg, T.B. 1982. Seasonal variations in fuel and fuel consumption by fires in a bluestem prairie. Ecology **63**:7-11.

Brown, J.K., and J.K. Smith. 2000. Wildland fire in ecosystems: effect of fire on flora. General Technical Report RMRS-GTR-42. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT.

Byram, G.M. 1959. Combustion of forest fuel. Forest Fire: control and use *in* K.P. Davis, editor. Pages pp. 61-89. McGraw-Hill, New York.

Cawson, J.G., and T.J. Duff. 2019. Forest fuel bed ignitability under marginal fire weather conditions in Eucalyptus forests. International Journal of Wildland Fire **28**:198-204.

Cheney, N.P., and J.S. Gould. 1997. Fire Growth and Acceleration. International Journal of Wildland Fire **7**:1-5.

Chiodi, A.M., N.K. Larkin, J.M. Varner, and J.K. Hiers. 2019. Sensitivity of prescribed burn weather windows to atmospheric dispersion parameters over southeastern USA. International Journal of Wildland Fire **28**:589-600.

Coppedge, B.R., S.D. Fuhlendorf, W.C. Harrell, and D.M. Engle. 2008. Avian community response to vegetation and structural features in grasslands managed with fire and grazing. Science Direct **141**:1196-1203.

Cordova, C.E., W.C. Johnson, R.D. Mandel, and M.W. Palmer. 2011. Late Quaternary environmental change inferred from phytoliths and other soil-related proxies: Case studies from the central and southern Great Plains, USA. Catena **85**:87-108.

Coughlan, M.R., and A.M. Petty. 2012. Linking humans and fire: a proposal for a transdisciplinary fire ecology. International Journal of Wildland Fire **21**:477-487.

Cruz, M.G., J.S. Gould, S. Kidnie, R. Bessell, D. Nichols, and A. Slijepcevic. 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.

Cruz, M.G., S. Kidnie, S. Matthews, R.J. Hurley, A. Slijepcevic, D. Nichols, and J.S. Gould. 2016. Evaluation of the predictive capacity of dead fuel moisture models for Eastern Australia grasslands. International Journal of Wildland Fire **25**:995-1001.

D'Antonio, C.M. 2000. Fire, Plant Invasions, and Global Changes. Invasive Species in a Changing World *in* H.A. Mooney and R.J. Hobbs, editors. Pages 65-93. Island Press, Washington, DC.

Daubenmire, R. 1968. Ecology of fire in grasslands. Advances in Ecological Research **5**:209-266.

Duff, T.J., R.E. Keane, T.D. Penman, and K.G. Tolhurst. 2017. Revisiting wildland fire fuel quantification methods: The challenge of understanding a dynamic, biotic entity. Forests **8**.

Edwards, E.J., C.P. Osborne, C.A.e. Stromberg, and S.A. Smith. 2010. The origins of C4 grasslands: Integrating evolutionary and ecosystem science. Science **328**:587-591.

Emery, S.M., and K.L. Gross. 2005. Effects of timing of prescribed fire on the demography of an invasive plant, spotted knapweed Centaurea maculosa. Journal of Applied Ecology **42**:60-69.

Engle, D.M., T.G. Bidwell, A.L. Ewing, and J.R. Williams. 1989. A technique for quantifying fire behavior in grassland fire ecology studies. Southwestern Association of Naturalists **34**:79-84.

Engle, D.M., S.D. Fuhlendorf, A. Roper, and J. David M. Leslie. 2008. Invertebrate community response to a shifting mosaic of habitat. Rangeland Ecology Management **61**:55-62.

Ewing, A.L., and D.M. Engle. 1988. Effects of late summer fire on tallgrass prairie microclimate and community composition. The American Midland Naturalist **120**:212-223.

Finney, M.A., and R.E. Martin. 1992. Calibration and field testing of passive flame height sensors. International Journal of Wildland Fire **2**:115-122.

Fuhlendorf, S.D., D.M. Engle, J. Kerby, and R. Hamilton. 2009. Pyric Herbivory: rewilding landscapes through the recoupling of fire and grazing. Conservation Biology **23**:588-598.

Fuhlendorf, S.D., W.C. Harrell, D.M. Engle, R.G. Hamilton, C.A. Davis, and J. David M. Leslie. 2006. Should heterogeneity be the basis for conservation? Grassland bird response to fire and grazing. Ecological Applications **16**:1706-1716.

Gagnon, P.R., K.E. Harms, W.J. Platt, H.A. Passmore, and J.A. Myers. 2012. Small-scale variation in fuel loads differentially affects two co-dominant bunchgrasses in a species-rich pine savanna. PLOS One **7**.

Gibson, D.J. 2009. Grasses and Grassland Ecology. Oxford University Press, Oxford, UK.

Gibson, D.J., D.C. Hartnett, and G.L.S. Merrill. 1990. Fire temperature heterogeneity in contrasting fire prone habitats: Kansas tallgrass prairie and Florida sandhill. Bulletin of the Torrey Botanical Club **117**:349-356.

Gibson, D.J., and L.C. Hulbert. 1987. Effects of fire, topography and year-to-year climatic variation on species composition in tallgrass prairie. Vegetatio **72**:175-185.

Grant, T.A., E.M. Madden, T.L. Shaffer, and J.S. Dockens. 2010. Effects of prescribed fire on vegetation and passerine birds in northern mixed-grass prairie. The Journal of Wildland Management **74**:1841-1851.

Gross, D.V., and J.T. Romo. 2010. Burning history, time of burning, and year effects on plant community structure and heterogeneity in Fescue prairie. Botany **88**:1-12.

Hawbaker, T.J., V.C. Radeloff, S.I. Stewart, R.B. Hammer, N.S. Keuler, and M.K. Clayton. 2013. Human and biophysical influences on fire occurrence in the United States. Ecological Applications **23**:565-582.

Higgins, K.F. 1984. Lightning fires in North Dakota grasslands and in pine-savanna lands of South Dakota and Montana. Journal of Range Management **37**:100-103.

Howe, H.F. 1994. Response of early- and late-flowering plants to fire season in experimental prairies. Ecological Applications **4**:121-133.

Howe, H.F. 1995. Succession and fire season in experimental prairie plantings. Ecology **76**:1917-1925.

Iverson, L.R., D.A. Yaussy, J. Rebbeck, T.F. Hutchinson, R.P. Long, and A.M. Prasad. 2004. A comparison of thermocouples and temperature paints to monitor spatial and temporal characteristics of landscape-scale prescribed fires. International Journal of Wildland Fire **13**:311-322.

James, S.R., R.W. Dennell, A.S. Gilbert, H.T. Lewis, J.A.J. Gowlett, T.F. Lynch, W.C. McGrew, C.R. Peters, G.G. Pope, A.B. Stahl, and S.R. James. 1989. Hominid use of fire in the lower and middle Pleistocene: A review of the evidence. Current Anthropology **30**:1-26.

Kalabokidis, K.D., and P.N. Omi. 1992. Quadrat analysis of wildland fuel spatial variability. International Journal of Wildland Fire **2**:145-152.

Keane, R.E. 2015. Wildland Fuel Fundamentals and Applications. 1st edition. Springer International Publishing.

Keane, R.E. 2016. Spatiotemporal variability of wildland fuels in US northern Rocky Mountain forests. Forests **7**.

Kerby, J.D., S.D. Fuhlendorf, and D.M. Engle. 2007. Landscape heterogeneity and fire behavior: scale-dependent feedback between fire and grazing processes. Landscape Ecology **22**:507-516.

Kidnie, S., and B.M. Wotton. 2015. Characterisation of the fuel and fire environment in southern Ontario's tallgrass prairie. International Journal of Wildland Fire **24**:1118-1128.

Kidnie, S.M. 2009. Fuel load and fire behaviour in the southern Ontario tallgrass prairie. M.S. University of Toronto, Toronto, CA.

Knapp, A.K., and T.R. Seastedt. 1986. Detritus accumulation limits productivity of tallgrass prairie. BioScience **36**:662-668.

LePage, Y., D. Oom, J.M.N. Silva, P. Jonsson, and J.M.C. Pereira. 2010. Seasonality of vegetation fires as modified by human action: observing the deviation from eco-climatic fire regimes. Global Ecology and Biogeography **19**:575-588.

Limb, R.F., T.J. Hovick, J.E. Norland, and J.M. Volk. 2018. Grassland plant community spatial patterns driven by herbivory intensity. Agriculture, Ecosystems and Environment **257**:113-119.

Loudermilk, E.L., J.K. Hiers, J.J. O'Brien, R.J. Mitchell, A. Singhania, J.C. Fernandez, W.P.C. Jr, and K.C. Slatton. 2009. Ground-based LIDAR: a novel approach to quantify fine-scale fuelbed characteristics. International Journal of Wildland Fire **18**:676-685.

Loudermilk, E.L., J.J. O'Brien, R.J. Mitchell, J. Wendell P. Cropper, J.K. Hiers, S. Grunwald, J. Grego, and J.C. Fernandez-Diaz. 2012. Linking complex forest fuel structure and fire behaviour at fine scales. International Journal of Wildland Fire **21**:882-893.

Matthews, S. 2014. Dead fuel moisture research: 1991-2012. International Journal of Wildland Fire **23**:78-92.

Miller, C., and D.L. Urban. 2000. Connectivity of forest fuels and surface fire regimes. Landscape Ecology **15**:145-154.

Mitchell, R.J., J.K. Hiers, J. O'Brien, and G. Starr. 2009. Ecological forestry in the Southeast: Understanding the ecology of fuels. Forest Ecology:391-397.

Morgan, P., C.C. Hardy, T.W. Swetnam, M.G. Rollins, and D.G. Long. 2001. Mapping fire regimes across time and space: Understanding coarse and fine-scale fire patterns. International Journal of Wildland Fire **10**:329-342.

Morvan, D., S. Meradji, and W. Mell. 2013. Interaction between head fire and backfire in grasslands. Fire Safety Journal **58**:196-203.

NWCG. National Wildfire Coordinating Group Glossary of Wildland Fire. PMS 205.

Oesterheld, M., J. Loreti, M. Semmartin, and J.M. Paruelo. 1999. Grazing, fire, and climate effects on primary productivity of grasslands and savanna. Ecosystems of the World: 16

Ecosystems of Disturbed Ground *in* L.R. Walker, editor. Pages p. 287-306. Elsevier, New York, NY.

Pausas, J.G., and J.E. Keeley. 2014. Abrupt climate-independent fire regime changes. Ecosystems **17**:1109-1120.

Pickett, S.T.A., and P.S. White. 1985. The ecology of natural disturbance and patch dynamics. revised edition. Academic Press, Inc., Orlando, FL.

Platt, W.J., S.L. Orzell, and M.G. Slocum. 2015. Seasonality of fire weather strongly influences fire regimes in south Florida savanna-grassland landscapes. PLOS One.

Power, M.J., J. Marlon, N. Ortiz, P.J. Bartlein, X. Wang, N. Williams, J. Wilmshurst, and J.H. Zhang. 2008. Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. Climate Dynamics **30**:887-907.

Pyne, S.J. 1984. Introduction to wildland fire: Fire management in the United States. 1st edition. John Wiley and Sons, New York, NY.

Ratajczak, Z., J.B. Nippert, J.M. Briggs, and J.M. Blair. 2014. Fire dynamics distinguish grasslands, shrublands and woodlands as alternative attractors in the central Great Plains of North America. Journal of Ecology **102**:1374-1385.

Rollins, M.G., R.E. Keane, and R.A. Parsons. 2004. Mapping fuels and fire regimes using remote sensing, ecosystem simulation, and gradient modeling. Ecological Applications **14**:75-95.

Roos, C.I., M.N. Zedeno, K.L. Hollenback, and M.M.H. Erlick. 2018. Indigenous impacts on North American Great Plains fire regimes of the past millennium. PNAS.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. Research Paper INT-115. USDA FS, Intermountain Forest and Range Experiment Station, Ogden, UT.

Ryan, K.C. 1981. Evaluation of a passive flame-height sensor to estimate forest fire intensity. Research Note PNW-390. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station.

Samson, F., and F. Knopf. 1994. Prairie conservation in North America. BioScience **44**:418-421.

Schultz, C.A., S.M. McCaffrey, and H.R. Huber-Stearns. 2019. Policy barriers and opportunities for prescribed fire application in the western United States. International Journal of Wildland Fire **28**:874-884.

Scott, J.H., and R.E. Burgan. 2005. Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model. RMRS-GTR-153. USDA Forest Service, Rocky Mountain Research Station.

Sousa, W.P. 1984. The role of disturbance in natural communities. Annual Review of Ecology and Systematics **15**:353-391.

Taylor, A.H., and C.N. Skinner. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecological Applications **13**:704-719.

Thaxton, J.M., and W.J. Platt. 2006. Small-scale fuel variation alters fire intensity and shrub abundance in a pine savanna. Ecology **87**:1331-1337.

Towne, E.G., and K.E. Kemp. 2008. Long-term response patterns of tallgrass prairie to frequent summer burning. Rangeland Ecology Management **61**:509-520.

Twidwell, D., S.D. Fuhlendorf, J. Charles A. Taylor, and W.E. Rogers. 2013. Refining thresholds in couple fire-vegetation models to improve management of encroaching woody plants in grasslands. Journal of Applied Ecology **50**:603-613.

Umbanhowar, C.E. 1996. Recent fire history of the northern Great Plains. The American Midland Naturalist **135**:115-121.

Umbanhowar, C.E. 2004. Interactions of climate and fire at two sites in the northern Great Plains, USA. Palaeogeography, Palaeoclimatology, Palaeoecology **208**:141-152.

Vakili, E., C.M. Hoffman, R.E. Keane, W.T. Tinkham, and Y. Dickinson. 2016. Spatial variability of surface fuels in treated and untreated ponderosa pine forests of the southern Rocky Mountains. International Journal of Wildland Fire **25**:1156-1168.

Viney, N.R. 1991. A review of fine fuel moisture modeling. International Journal of Wildland Fire **1**:215-234.

Weir, J.R. 2011. Are weather and tradition reducing our ability to conduct prescribed burns? Rangelands **33**:25-30.

Whelen, R.J. 1995. The Ecology of Fire. Cambridge University Press, Cambridge, England, UK.

Whitlock, C., P.E. Higuera, D.B. McWethy, and C.E. Briles. 2010. Paleoecological perspectives on fire ecology: revisiting the fire-regime concept. The Open Ecology Journal **3**:6-23.

Wiggers, M.S., L.K. Kirkman, R.S. Boyd, and J.K. Hiers. 2013. Fine-scale variation in surface fire environment and legume germination in the longleaf pine ecosystem. Forest Ecology and Management **310**:54-63.

Yoder, J., D. Engle, and S. Fuhlendorf. 2004. Liability, incentives, and prescribed fire for ecosystem management. Frontiers in Ecology and the Environment **2**:361-366.

Yurkonis, K.A., J. Dillon, D.A. McGranahan, D. Toledo, and B.J. Goodwin. 2019. Seasonality of prescribed fire weather windows and predicted fire behavior in the northern Great Plains, USA. Fire Ecology **15**.

Zedler, P.H. 2007. Fire effects on grasslands. Plant Disturbance Ecology - The process and the response *in* E.A. Johnson and K. Miyanishi, editors. Pages 397-439. Academic Press, Burlington, MA.

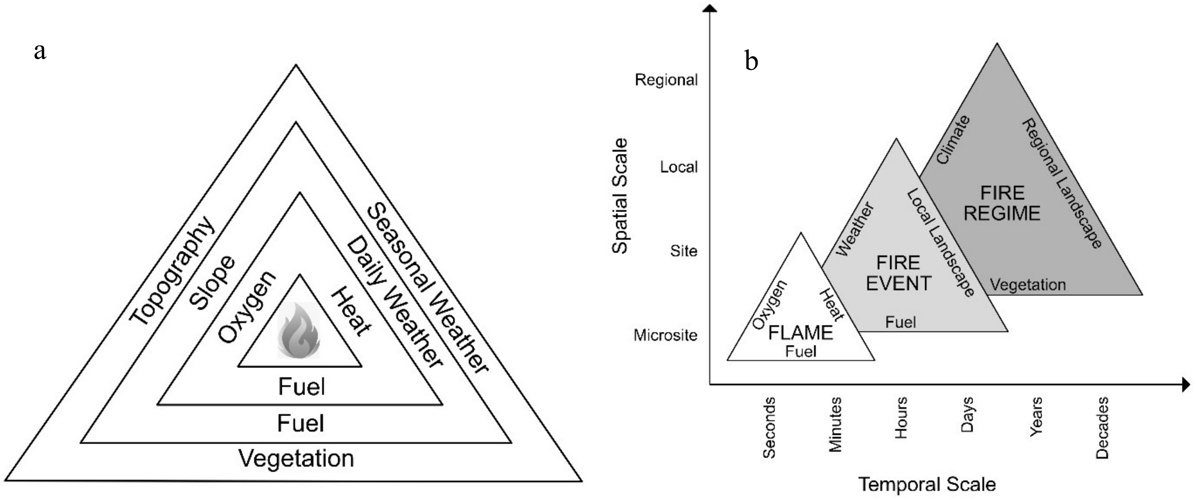

Figure 1. Conceptualized fire behavior triangles as adapted from Keane (2015, a) and Whitlock (2010, b) where each side of an equilateral triangle represents a dominant factor that affects fire at their respective spatial and temporal scales.

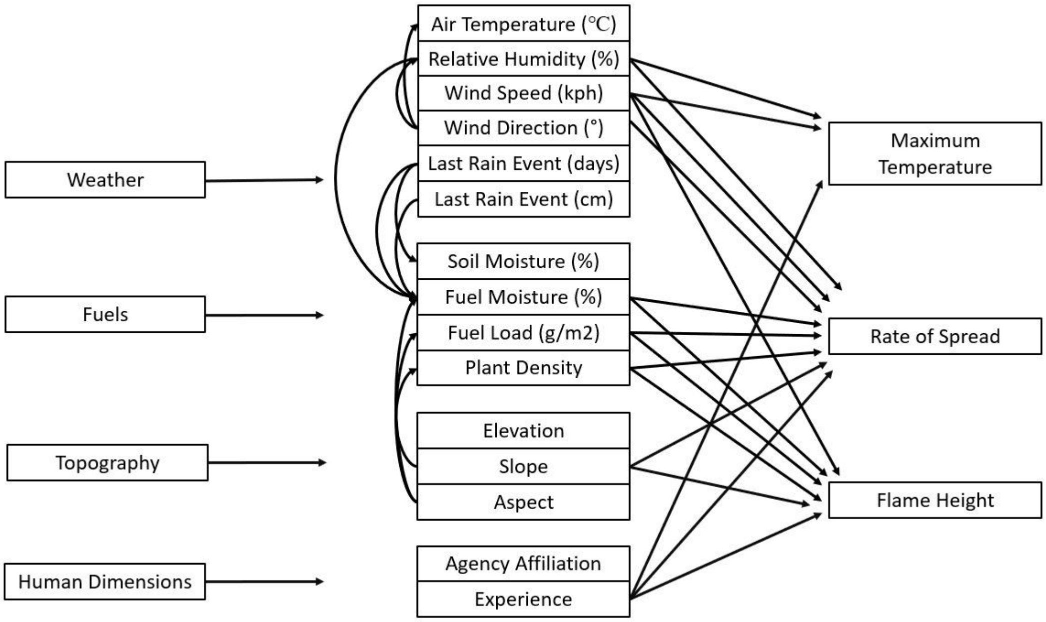

Figure 2. Flowchart of the hypothesized relationships among explanatory fuel and weather variables and their effects on fire behavior.

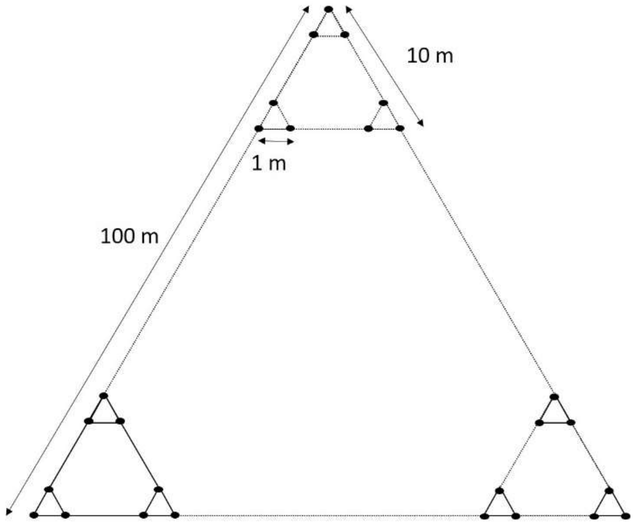

Figure 3. Sample points were arranged into nested 1, 10, and 100 m sided triangles in a Sierpinski Triangle formation centered within a prescribed burn unit.

EFFECTS OF FUELS AND WEATHER ON FIRE BEHAVIOR IN NORTH DAKOTA GRASSLANDS

Abstract

Interactions among site topographic, fuel, and weather characteristics during ignition strongly affect prescribed fire behavior. To further our understanding of prescribed fire behavior in the northern Great Plains, we quantified fuel and weather characteristics associated with 27 prescribed fires conducted across three sites in North Dakota. We determined the maximum temperature, flame height, and the rate of fire spread associated with advancing fire fronts on each fire with a series of 27 nested sample points. Fuel and weather characteristics associated with fires were similar between two climatologically and vegetatively different sites. The rate of fire spread and flame height were most strongly correlated with fuel and soil moisture, dew point, wind speed, and days since and quantity of the last rainfall. Maximum temperature was correlated only with fuel and soil moisture. Ultimately, fire behavior was similar between the stations having burned under similar fuel bed properties and weather conditions. Maximum temperature and flame height was best predicted by fuel moisture, relative humidity, and quantity of the previous rainfall event. Rate of spread was best predicted by dew point, wind speed, and quantity of the last rain event. Not surprisingly, increased fuel moisture and relative humidity suppressed fire behavior. However, there was a positive effect of the amount of the previous rainfall event on fire behavior responses. Collectively, these outcomes suggest that fire managers need not question the effect of seasonality on fire behavior, but rather focus on executing fires whenever possible during seasonally available windows. These efforts address the paucity of basic fire science in the northern Great Plains and support management decision-making across the region.

Introduction

Fire is an integral ecological process responsible for the maintenance of terrestrial biomes around the world (Bond and Keeley 2005). Fire can affect community composition and ecosystem structure and function (Morgan et al. 2001, Pausas and Keeley 2019). Without fire, fire-adapted ecosystems like grasslands are more susceptible to invasion by non-native plant species and woody shrubs (Briggs et al. 2005, DeSantis et al. 2011, Wragg et al. 2017). Fire has been recognized as essential for grassland conservation (Hovick et al. 2017) and prescribed fire management has been increasingly used to mimic natural fire processes (Kolden 2019). Given that the application of prescribed fire involves human decision-making, it is likely that fires range in their intensity and behavior depending on the agency conducting the fire. Unfortunately, while much prescribed fire research has focused on first- and second-order fire effects (Ewing and Engle 1988, Biondini et al. 1989, Hovick et al. 2017), few have considered the nature of the fire itself when characterizing the effects of prescribed fires on grassland ecosystems (Reinhardt et al. 2001, Hyde et al. 2013, Strong et al. 2013).

Fire managers must consider the interactions among site topographic features, site fuel characteristics, and forecasted weather conditions when executing a fire. Objective-based management involves articulating ideal environmental conditions suitable for the ignition, propagation, and development of a fire event (Parisien and Moritz 2009). Fire development, the continued propagation and combustion process after the initial ignition, is most affected by fuel moisture (Morvan 2013) as it sets the threshold for the quantity of energy required to dry fuels to the point that they combust (Marsden-Smedley and Catchpole 2001, Cruz et al. 2016). Wetter fuels require a greater energy input to reach combustion and can result in lower intensity fires as the rate of spread decays and less radiant energy is released (Marsden-Smedley and Catchpole

2001, Morvan 2013, Cruz et al. 2015). Because grasslands lack an overstory canopy and consist of relatively fine fuels, fuel moisture can be highly variable and respond quickly to changing weather conditions (Cruz et al. 2016). Fuels can quickly dry as air temperatures increase, relative humidity decreases, and under higher sustained winds (Verdu et al. 2012).

Recognizing the effect of weather on fuel moisture, managers must articulate their ideal weather conditions for applying prescribed fire when creating objective-based prescription burn plans (Andrews and Queen 2001, Reinhardt and Dickinson 2010). Ideal fuel and weather conditions for effective prescribed fire may vary spatially and temporally and are often concentrated within a small window of available burn days at the beginning and end of the growing season in the North American Great Plains (Weir 2011, Yurkonis et al. 2019). Although managers may articulate a fairly wide range of acceptable weather conditions, the decision to attempt a fire or not is commonly driven by arbitrary suggestions, tradition, and employees' regional experience (Yoder et al. 2004, Chiodi et al. 2019) and is further constrained by regulatory mandates and resource availability (Quinn-Davidson and Varner 2012, Chiodi et al. 2019, Schultz et al. 2019). This multi-faceted decision making coupled with increased regulatory constraints dictate that fire managers apply prescribed fire under conditions that result in low-intensity fires than what would have occurred historically (Twidwell et al. 2013). Managers are more apt to conduct fire operations under marginal weather conditions when fires are more easily controlled, such as those in the early growing season (Cawson and Duff 2019). This may be problematic for propagating fires, as greener fuel beds contain higher fuel moisture content. While potentially better for yielded a stronger ecological effect, late growing season fires are more difficult to control or suppress due to drier fuel moisture. These fires yield faster forward rate of spread and higher fireline intensities (LePage et al. 2010).

Although managers may apply fire under more conservative conditions, advancements in fire forecasting enable fire managers to evaluate the potential range of fire behavior under a range of circumstances (Andrews and Queen 2001, Quinn-Davidson and Varner 2012). Modern operational fire behavior models incorporate a broader range of environmental parameters with extensive inputs for site characteristics, fuel bed assessments, and forecasted weather conditions. Guiding objective-based prescriptions or suppression operations, fire models may also perform risk assessment, examine fuel treatment options and potential fire effects (Andrews and Queen 2001). Improved fire behavior simulations, particularly those conducted outside of fully cured fuel conditions (Scott and Burgan 2005, Mell et al. 2007) can better guide and evaluate fire management practices.

To further our understanding of fire behavior in the northern Great Plains, we quantified fuel and weather conditions associated with the behavior of prescribed fires in North Dakota. This study addressed the following questions:

1. Do fuel and weather conditions under which prescribed fires are preformed vary among stations?
2. Does fire behavior vary among stations?
3. What combination of *a priori* determined fuel and weather variables best describes observed fire behavior in this region?

We hypothesized prescribed fires across three ecoregions of North Dakota would produce different fire behavior because of differences in local fuel and weather conditions. We also hypothesized maximum temperature, flame height, and rate of spread would correlate with weather conditions (wind speed and relative humidity) and fuel conditions (fuel load and fuel moisture). These efforts both address the paucity of basic fire science in the northern Great Plains and support management decision-making across the region.

Methods

Study Sites

We sampled 27 prescribed fires conducted in three sites in northeastern, central, and southwestern North Dakota, USA that span a precipitation and vegetation composition gradient (Figure 1). In the northeast, we sampled one fall (October) fire and one spring (June) on Oakville Prairie (hereafter Oakville; centroid 47.902931, -97.315312; Emerado, ND), a 453-ha site jointly managed by the University of North Dakota and the North Dakota Game and Fish Department. Located in the Glacial Lake Agassiz basin, this site primarily consists of remnant tallgrass alkaline prairie and receives the highest average precipitation (55.1 cm) of the three study sites (Hadley 1970). Oakville is a relatively flat site (mean slope between the centroids of adjacent management units = 0.46° ± 0.05°). Lowland soils are of the Ojata series and are characterized by high salinity. Upland soils are primarily of the Antler series and have moderate to low salinity (Aandahl 1982). Fire-carrying fuels are predominantly comprised of dense herbaceous grass and forbs ranging 0.5-2 m in height (Deal 2016). Historically, plant communities of the site were defined by the presence of *Spartina pectinata* (prairie cordgrass), *Pascopyrum smithii* (western wheatgrass), *Poa pratensis* (Kentucky bluegrass), *Andropogon gerardii* (big bluestem), and *Distichlis spicata* (saltgrass) (Hadley and Buccos 1967). We began managing Oakville with prescribed fire in 2014 after nearly 70 years of little to sporadic fire and haying management (Hadley 1970, Redman 1972). In doing so, we divided the site into seven, 66 ha management units and aimed to incorporate fall fires with a four-year return interval. For the purpose of this study, we sampled the first fires on Unit D (west half of section 16) in 2017 and Unit F in 2019. The last known fire before these occurred in the early 1990s (Seabloom, pers comm May 2019) and the site had no recent grazing history.

In central North Dakota, we sampled 15 spring (May) fires in two pastures at the Central Grassland Research Extension Center (hereafter CGREC; site centroid 46.718686, -99.448521, Streeter, ND) managed by North Dakota State University. Located in the Missouri Coteau ecoregion, this 2158 ha site contains 461 ha of remnant and improved mixed-grass prairie and receives moderate annual precipitation (46.7 cm). Grasslands receiving fire treatment at CGREC are divided into two 259 ha pastures, Barker and Bob, both named after previous employees. Topography exhibits irregular rolling and undulating hills created by historic glacial events (Bluemle 1991, Limb et al. 2018). Elevation across the Barker pasture (centroid 46.725796, -99.437877) varies from 594–615 m above sea level but can vary 3–12 m feet within burn units. Elevation decreases by 30 m from north to south across the Bob pasture (centroid 46.771358, -99.479609) and varies 6–12 m within burn units. The soils in both pastures formed from glacial till and are dominated by Zahl soil series interspersed with hills capped by Wabek and Williams soil series (Aandahl 1982). The site is dominated by *Pascopyrum smithii*, *Nassella viridula* (green needlegrass)*, Poa pratensis*, *Bromus inermis* (smooth brome)*, Koeleria macrantha* (junegrass), *Artemisia spp.*, and *Solidago spp.* and includes dense aggregations of *Glycyrrhiza lepidota* (wild licorice) and *Symphoricarpos occidentalis* (western snowberry) (Limb et al. 2018). CGREC introduced small fire treatments in 2015 and initiated pyric herbivory studies in 2017. The pyric herbivory treatments involve applying 8 or 16 ha prescribed fires to 68 ha (one quarter section) of each pasture in either spring or summer. Pastures are then grazed at a stocking density of six acres per cow-calf pair. The combined fire and grazing treatments promoted substantial variability and discontinuity of available fuels. Spring prescribed fires at CGREC were ignited as soon as fuels were dry and appropriate weather conditions were met (increased wind speeds, lower relative humidity).

In southwestern North Dakota, we sampled ten fall (October) fires in two pastures at the Hettinger Research Extension Center (hereafter, HREC; site centroid 46.004443, -10.646477, Hettinger, ND) managed by North Dakota State University. This 457 ha site on the Missouri Plateau consists of improved short-grass prairie and receives low annual precipitation (38 cm). Grasslands of HREC are divided into two pastures, Clements (145 ha) and Fitch (255 ha). The Clements pasture (centroid 45.80975, -102.62152) is located at the base of a butte and exhibits rolling topography with an elevation of 807–826 m. Soils are equally dispersed amongst Belfield, Harriet, and Vebar series (Aandahl 1982). The Fitch pasture (centroid 46.039228, -102.720617) is relatively level and exhibits an elevation of 841–859 m. Well-drained Vebar soils dominate this pasture. Poorly drained soils of the Harriet series are located at the lowest elevations with Belfield series interspersed throughout the pasture. The pastures were formerly enrolled in the USDA NRCS Conservation Reserve Program and are dominated by the introduced species *Thinopyrum intermedium* (intermediate wheatgrass), *Bromus inermis*, *Medicago sativa* (alfalfa), *Agropyron cristatum* (crested wheatgrass), and *Poa pratensis* (Spiess, pers comm May 2019). HREC incorporated pyric herbivory management in 2017, applying prescribed fire to one 16 ha (40 acre) section of each pasture annually. Pastures are then subject to season-long grazing by cattle (25 cow-calf pairs per pasture) and sheep (215 ewes). As a result of the of the season-long grazing, this site had the lowest fuel quantity across all three sites. At HREC we ignited fires succeeding the first seasonal frost, but prior to the first snowfall event.

Across all three sites, fire ignitions occurred between 1200 and 1600. Crews used flanking fires along the perimeter of the management units closely followed by backfire ignitions. We used head fires in units with consistent fuels and flanking strip ignitions in units with more heterogeneous fuels. Fires at Oakville were conducted under two different burn bosses (W. Brown, Badger Creek Wildfire, Poplar, MT and B. Keller, Prairie Restorations, Inc, Moorhead, MN). Fires at CGREC and HREC were overseen by the same burn boss (D. McGranahan, NDSU Wildland Fire, Fargo, ND).

Data collection

We measured fuels and fire behavior (Table 1) within each fire with a predetermined set of 27 sample points arranged into nested equilateral triangles (Sierpinski fractal triangle formation; Figure 2; (Dorrough et al. 2007)). We began by positioning a 100 m sided equilateral triangle in the center of each burn unit. We then nested a 10 m sided triangular subplot into each vertex of the 100 m sided triangle (3- 10 m triangles = 1 - 100 m triangle) and nested a 1 m sided triangular subplot into each vertex of each 10 m sided triangle (9 – 1 m sided triangles = 3 – 10 m triangles = 1 100 m triangle). We then sampled fuels and fire behavior at each vertex of each of the nine nested 1 m triangles (3 sample points × 9 1 m triangles = 27 sample points/plot). This sampling design allowed us to sample fire behavior irrespective of the direction of the flame front as it moved through the study area (Simard et al. 1984).

Fuel and weather conditions

We measured fuel conditions at each sample point no more than three hours prior to fire ignition. We quantified fuel load by recording the overhead leaf area per unit ground area (Leaf Area Index, LAI; AccuPAR LP-80 ceptometer, Pullman, WA) at the soil surface at each sample point. We quantified soil moisture by recording the soil Volumetric Water Content (VWC; Field Scout TDR-100, Aurora, IL) at each sample point as an in-field proxy for fuel moisture (Krueger et al. 2015). We additionally quantified fuel moisture through destructive sampling of all fuels in a 25 × 25 cm quadrat 0.5 m away from each sample point array. Fuel samples were placed in airtight plastic bags to retain moisture, weighed, dried to constant mass at 60 ºC for 48 hours, and weighed again. Initial and final fuel masses were used to calculate percent fuel moisture content.

We downloaded hourly wind velocity (kph), maximum wind speed (kph), relative humidity (%), dew point (°C), date and quantity (cm) of previous precipitation records for each fire event from the NDAWN database for the weather station nearest to each site (North Dakota Agricultural Weather Network, NDAWN). NDAWN provided the most convenient and readily available weather data for the local area. The Hettinger NDAWN station is 0.70 miles from the research station (1.94 – 4.95 miles from the fires). The Streeter station is located on CGREC, in the pasture directly west of the facilities (0.58 – 4.47 miles from the fires). The NDAWN station at Grand Forks is the farthest from the research fires at 12.58 miles east-southeast of Oakville.

Fire Behavior

To monitor each fire flame front, we equipped each 1 m triangle of three sample points with an Arduino-based datalogger and three K-type thermocouples (high temperature Iconel overbraided ceramic fiber insulated, Omega, Norwalk, CT). Dataloggers were assembled from Adafruit (Adafruit Industries, LLC, New York City, NY) components and housed inside water-resistant Pelican (Pelican Products, Inc, Torrance, California) cases. Each thermocouple was positioned 15 cm above the soil surface. We shielded all fire-sensitive instrumentation with metal duct covers. Each datalogger was set to record the temperature (ºC) registered by each thermocouple at 0.5 sec intervals for the duration of the fire event. From these data we queried the maximum temperature (ºC) and time of maximum temperature as the flame front passed each sample point. We calculated the direction (°) and rate of spread (m/s) of the flame front as it passed through each 1 m, 10 m, and the overall 100 m triangle using the maximum temperature timestamps following equations 1 and 2 from Simard et al. (1984).

To quantify absolute flame height, we suspended flame retardant string on a metal stand at each sample point following Ryan (1981) and Finney and Martin (1992) on 22 of the 27 fires. To prepare the flame retardant strings, we soaked 16 ply, 100% cotton string in 1:1 ratio solution of monoammonium phosphate for 24 hours and then oven dried them at 60 °C for 24 hours. At deployment, the total string height was set above the predicted flame height as determined by the fuel load. After the fire event, we removed, scored, and measured the remaining string. We recorded the height at which each string was "broken", the height where there was a distinct break by disintegrated or brittle fibers when string is bent or burned through. We additionally recorded the height to which strings were "blackened", exhibiting a thoroughly black circumference, and, "charred", defined as a higher point where no natural string color remained, *i.e.*, light brown color around string circumference. To calculate absolute flame height, defined as the height of the flame base to the top of the continuous flame (Ryan 1981), we subtracted the charred length from the total string length.

Data Analysis

We used Principle Component Analysis (PC-ORD, ver. 7, MjM Software Design, Gleneden Beach, OR) to separately visualize differences in fuel (4 explanatory variables) and weather (6 explanatory variables) datasets summarized at the fire event scale (one value/fire event = average across all 27 sample points). We used a Multi-Response Permutation Procedure (MRPP) based on a Euclidian distance matrix to test for pairwise differences in fuel and weather conditions prior to ignition between CGREC and HGREC, the two stations with numerous fires. Due to a skewed distribution, we natural log-transformed rate of spread. We used nested mixed model ANOVA (procMixed; SAS Studio, SAS Institute Inc., Cary, NC, USA) to test for fixed station effects on fire behavior (maximum temperature, flame height, and rate of spread) at the fire event scale as well (27 values = one average value per fire). For this analysis, we included station as a fixed term and fire event nested in station as a random term to account for the nested sampling design. To evaluate first order main effects of station, fuel covariates (fuel load, soil moisture, fuel moisture), and weather covariates (dew point, relative humidity, wind speed, and quantity of previous precipitation event) on fire behavior summarized at the fire event scale, we constructed a suite of 65 candidate linear mixed models that contained 0 to 6 covariate terms (lme4; Bates et al. 2015) for each response variable (maximum temperature, flame height, rate of fire spread) (R Core Team, 2020, Vienna, Austria). Fires at Oakville were omitted due to the small sample size, as were any fires missing fuel data. All explanatory fuel and weather covariates and fire rate of spread were standardized, but not centered. We confirmed all other response variables were characterized with a gaussian distribution. Models were analyzed using Maximum Likelihood methods, as AICcmodavg (Mazerolle, 2019) does not recognized mixed models analyzed under Restricted Maximum Likelihood Methods. We identified five competing models based on lowest AICc scores, model weight, cumulative weight, and log-likelihood and used model averaging to compute estimates and 95% confidence intervals associated with their model terms (AICcmodavg; Mazerolle, 2019). Parameter estimates and 95% confidence intervals were compiled by averaging across the top two models, therefore not requiring an ANOVA to test the difference between top competing models.

Results

Over the three-year period, we attempted 29 ignitions, and this resulted in 27 propagated fires. Fires were ignited using backing and flanking fires prior to igniting head fires. Some fires (fire events 22–24) required strip ignitions due to low fuel continuity. Due to logistical limitations with data collection, we had a full fuel dataset for 19 of the 27 prescribed fires and a full weather dataset for 24 of the 27 fires.

Fuel conditions

The first two axes of the fuel PCA (Figure 3a, b) explained 88.4% of the cumulative variance in the four-variable fuel dataset. Fuel load (r = 0.909), soil moisture (r = -0.879), and fuel moisture (r = 0.220) were strongly correlated with the first axis (54.9% variance explained). Fuel moisture (r = 0.969) and soil moisture (r = -0.254) were strongly correlated with the second axis (33.5% variance explained). Field stations separated on the first axis in that Oakville had a higher fuel load than CGREC and HREC. CGREC separated from HREC on the second axis, but fuels were overall similar between the two prior to ignition (MRPP Pairwise A = -0.002 p = 0.390). No fire behavior variables were strongly correlated (r = 0.20) with the first axis. Maximum temperature (r = -0.300), rate of spread (r = -0.222), direction of the flame front (r = -0.232), and flame height (r = -0.301) were correlated with the second axis.

Weather conditions

The first three axes of the weather PCA explained 79.7% of the cumulative variance in the six-variable weather dataset (Figure 3c, d). Dew point ($r = -0.836$), wind speed ($r = 0.451$), days since last rainfall ($r = 0.637$) and quantity of last rainfall ($r = -0.620$) were correlated with the first axis (33.9% variance explained). Dew point ($r = 0.330$), relative humidity ($r = 0.790$), wind speed ($r = 0.640$), and quantity of last rainfall ($r = -0.329$) were correlated with the second axis (25.1% variance explained). Station separation on the first and second axes reflect spring burning at CGREC and fall burning at HREC, but overall, weather conditions for the fire events were similar between CGREC and HREC ($A = 0.025$, $p = 0.162$). Rate of spread ($r = 0.486$) and flame height ($r = 0.208$) was correlated with the first axis, but maximum temperature was not strongly ($r < 0.20$) correlated with the main axis of variation in weather conditions. All fire behavior variables were not strongly ($r < 0.20$) correlated with the second axis of variation in weather conditions.

Fire behavior

Fire behavior responses (maximum temperature, flame height, and rate of spread) were similar between stations at the fire event scale (Table 2; Figure 4). Maximum temperature and flame height responses were best predicted by a combination of fuel bed characteristics and weather conditions at the time of ignition (Tables 3, Figure 5). The top models for maximum temperature and flame height were nearly identical, both included fuel moisture, relative humidity, and quantity of last rainfall. Maximum temperature and flame height were positively affected by decreased quantities of previous rainfall events, but negatively affected by increased values of relative humidity and fuel moisture. Dew point was not statistically significant but may affect negatively affect flame height. However, rate of spread was solely determined by weather conditions at the time of ignition (wind speed, relative humidity, and quantity of last rainfall;

Figure 5). Increased wind speed and quantity of last rainfall significantly increased rate of fire spread, whereas increased humidity will decrease spread rates.

Discussion

Although fire managers draft prescriptive burn plans, it is rare for managers to retroactively evaluate fuel and weather conditions under which the fire was conducted. It is even rarer to relate those conditions to the observed fire behavior yielded by the fire event. We assessed the fuel bed and weather conditions at the time of ignition for a series of prescribed fires across North Dakota and related them to the observed fire behavior. We found fuel and weather conditions to be similar among fires and stations. This was further supported as we found no evidence of a station effect in fire behavior. This would suggest that some concern over details of the environmental conditions at the time of ignition, particularly seasonality, may not be warranted. The best models predicted weather variables and fuel moisture are most likely to significantly affect fire behavior in northern grasslands.

Regardless of their location across the state and different managerial treatments (grazing, fire frequency, seasonal fire application), fuel bed properties were relatively similar among field stations. As tallgrass prairie, Oakville contained more biomass that contributed to a larger fuel load than CGREC and HREC. However, fuel properties as we measured them were similar between CGREC and HREC at the time of ignition. Although fuel moisture was very strongly correlated with the second PCA axis, fuel moisture was similar between field stations despite seasonal differences in fire application. This likely relates to the nature of the fuels at these sites. Both sites are dominated by cool-season grasses, known for growth both early and late season and their contributions to increasing fuel moisture during their extended growing periods (McGranahan et al. 2012). CGREC contains fuels derived from a mixture of warm- and cool-season grass species. HREC primarily contains fuels derived from cool-season grasses. While functional groups may affect fuel moisture, weather conditions leading to a fire event may also play a role.

Weather conditions during fire events were also similar among field stations despite seasonal differences in ignitions. In North Dakota, two seasonal weather windows exist with fairly similar conditions (Yurkonis et al. 2019). It appears that managers are operating in both seasonal spaces. Actual operating weather windows across all three stations were relatively comparable to acceptable fire weather conditions as outlined by Weir (2011) and Yurkonis et al. (2019). Upper thresholds included wind speeds of 23 kph, fuel moisture content of 93% (averaged 48%), and relative humidity of 57%. Marginal fire weather conditions such as low wind speeds, high relative humidity, and lower temperatures are more likely to result in unburned fuels or low to moderate fireline intensities (Cawson and Duff 2019).This would suggest regional fire managers are fairly consistent in selecting for specific fuel and weather conditions. Burning under the same fuel and weather conditions may generate consistent fire behavior, thus potentially yielding similar fire effects.

Fires were of intermediate temperatures and shorter flame heights. Maximum temperature data align with previously reported figures collected within the Great Plains. Maximum temperatures on the fires in our study averaged 227.26 ± 94.74°C. Fires in South Dakota grasslands averaged ≥ 375°C (Ohrtman et al. 2015). Bailey and Anderson (1980) recorded temperatures of 186 ± 10°C in grasslands of Alberta. The observed flame heights were relatively shorter than previously described in the literature. Our flame heights were on average

0.4 ± 0.3 m, which is comparable with average flame heights of backfires at Konza Prairie (0.3 ± 0.2 m) and in a South African savanna (0.9 ± 0.1 m; Trollope et al., 2002). Flame heights from head fires within Konza Prairie (Manhattan, Kansas) average 3.7 ± 4.3 m (Trollope et al. 2002). This difference is likely attributable to differences in fuel structure. The central Great Plains region is comprised of warm-season grasses that are exposed to a longer growing season and increased precipitation than grasslands of North Dakota. Taller fuels can contribute to increased flame heights due the physiological plant structure. The quantity of biomass also yields more fuels available for consumption and therefore increases energy output. Rate of fire spread within North Dakota averaged 4.47 ± 3.82 m/min (0.07 ± 0.064 m/s). These values are significantly slower than head fires of Konza Prairie, which averaged 32.4 ± 18 m/min (0.54 ± 0.3 m/s), or South African savannas at 22.8 ±13.2 m/min (0.38 ± 0.22 m/s; (Trollope et al. 2002)). However, the rate of spread is faster than the values reported for backfires at both locations. Bidwell and Engle (1992) recorded fire spread averaging 6 m/min (0.1 m/s) on prescribed grassland fires of Oklahoma.

Based up on our *a priori* measured characteristics of the fire environment, the PCA analysis found most fuel bed properties and weather conditions at the time of ignition were weakly correlated with the fire spread rate. However, maximum temperature and flame height were correlated with fuel moisture, wind direction, date, and quantity of precipitation from the previous rain event. The analysis indicated that fuel bed properties and weather conditions were relatively similar across seasons and did not differ as much as previously thought.

The PCA also revealed rate of fire spread was weakly correlated with fuel density, soil moisture, and fuel load. The likelihood of sustained ignition, and furthermore successive propagation, can be affected by fuel arrangement (bulk density and continuity) (Cawson and

Duff 2019). Cruz et al. (2018) found fuel load and rate of fire spread in grassland ecosystems of eastern Australia to be inversely related. The effect of fuel moisture on fire rate of spread may be concealed by weather conditions such as wind speed (Cheney et al. 1993, Cruz et al. 2018).

Model selection (lowest AICc, highest AICc weight) identified fuel moisture, relative humidity, and quantity of last rainfall as the best predictors of maximum temperature and flame height (Table 3). Rate of fire spread was best explained by dew point, wind speed, and quantity of the last rainfall event. These findings supported our hypothesis that these response variables would correlate with explanatory variables previously identified in the literature such as wind speed, relative humidity, and fuel moisture. We suspect the drought of 2018 was responsible for delayed rain fall events, decreased relative humidity, and therefore over lower fuel moisture content. Fuel moisture content significantly affects rate of spread (Morvan, 2013; Cruz et al., 2015).

At the most basic conceptual level, fire cannot propagate without fresh oxygen and fuels. Heat is transferred to unburned fuels via wind, thus raising the temperature required for ignition. This also provides an influx of fresh oxygen molecules to continue the chemical combustion process. Research findings from Cheney and Gould (1997) state fireline geometry also has implications for fire behavior, specifically rate of fire spread and flame height. The peak of parabolic fireline geometries will travel parallel with the wind direction, thereby generating faster rates of spread. However, the rate of spread on fireline sides are more susceptible to aspiration by fluctuating winds as they can travel perpendicularly to wind direction and the associated convective heat transfer (Morvan et al. 2009). Therefore, it is possible the size of the burn unit and therefore ignition techniques may have contributed to the variable rates at which fires traveled on the landscape and passed through the sensor arrays.

Overall, fire behavior was similar across seasons, despite being confounded by the date at which fires were ignited at the station. Inherently, properties of the fuel bed and weather conditions were similar among stations and therefore seasons. However, if the objective is to generate specific fire behavior, the conditions of the fuel bed and weather window matter to a point. Regardless of the conditions, fire managers in the northern Great Plains should expand upon their current traditions to get fire on the ground. Burning under variable fuel and weather conditions will generate different ecological effects with the changes in fire behavior and severity. Changing ignition techniques to incorporate different flame geometries may better meet ecological objectives. Our understanding of prescribed fire and its resulting behavior has consequences for fire-dependent grassland ecosystems. We must better understand the relationships between fuels, weather, and fire behavior.

Acknowledgements

Personnel from Badger Creek Wildfire (Poplar, MT), Prairie Restorations, Inc, (Moorhead, MN), NDSU Wildland Fire (Fargo, ND), and the North Dakota Agricultural Experiment station assisted with prescribed fire preparation, planning, and operations. the Oakville Prairie Field Station committee. L. LaFond, C. LaFond, and E. Wahl assisted with datalogger assembly. M. Lakey, J. Spiess, J. Cutter, and A. Steele assisted with sensor deployment and data collection. Funding for components and materials was made available through the Biology Departmental Research Committee. Funding to attend and present at conferences was awarded through the departmental Academic Programs and Student Awards

Committee (APSAC) Research Stipend. Lastly, many thanks to B. Darby, who endlessly answers all my statistics and modeling questions.

Literature Citations

Aandahl, A.R. 1982. Soils of the Great Plains: land use, crops, and grasses, Lincoln, NE.

Andrews, P.L., and L.P. Queen. 2001. Fire modeling and information system technology. International Journal of Wildland Fire **10**:343-352.

Bailey, A.W., and M.L. Anderson. 1980. Fire Temperatures in Grass, Shrub and Aspen Forest Communities of Central Alberta. Journal of Range Management **33**:37-40.

Bidwell, T.G., and D.M. Engle. 1992. Relationship of Fire Behavior to Tallgrass Prairie Herbage Production. Journal of Range Management **45**:579-584.

Biondini, M.E., A.A. Steuter, and C.E. Grygiel. 1989. Seasonal fire effects on the diversity patterns, spatial distribution and community. Vegetatio **85**:21-31.

Bluemle, J.P. 1991. The Face of North Dakota. Revised edition. Bismarck Educational Series 21, North Dakota, USA.

Bond, W.J., and J.E. Keeley. 2005. Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems. TRENDS in Ecology and Evolution **20**.

Briggs, J.M., A.K. Knapp, J.M. Blair, J.L. Heisler, G.A. Hoch, M.S. Lett, and J.K. McCarron. 2005. An ecosystem in transition: Causes and consequences of the conversion of mesic grassland to shrubland. BioScience **55**:243-254.

Cawson, J.G., and T.J. Duff. 2019. Forest fuel bed ignitability under marginal fire weather conditions in Eucalyptus forests. International Journal of Wildland Fire **28**:198-204.

Cheney, N.P., and J.S. Gould. 1997. Fire Growth and Acceleration. International Journal of Wildland Fire **7**:1-5.

Cheney, N.P., J.S. Gould, and W.R. Catchpole. 1993. The influence of fuel, weather and fire shape variables on fire-spread in grasslands. International Journal of Wildland Fire **3**:32-44.

Chiodi, A.M., H.K. Larkin, J.M. Varner, and J.K. Hiers. 2019. Sensitivity of prescribed burn weather windows to atmospheric dispersion parameters over southeastern USA. International Journal of Wildland Fire **28**:589-600.

Cruz, M., A. Sullivan, J. Gould, R. Hurley, and M. Plucinski. 2018. Got to burn to learn: the effect of fuel load on grassland fire behaviour and its management implications. International Journal of Wildland Fire **27**:727-741.

Cruz, M.G., J.S. Gould, S. Kidnie, R. Bessell, D. Nichols, and A. Slijepcevic. 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.

Cruz, M.G., S. Kidnie, S. Matthews, R.J. Hurley, A. Slijepcevic, D. Nichols, and J.S. Gould. 2016. Evaluation of the predictive capacity of dead fuel moisture models for Eastern Australia grasslands. International Journal of Wildland Fire **25**:995-1001.

Deal, B.W. 2016. Plant and arthropod associations with environmental gradients in a northern tallgrass prairie. Master of Science. University of North Dakota, Grand Forks, ND.

DeSantis, R.D., S.W. Hallgren, and D.W. Stahle. 2011. Drought and fire suppression lead to rapid forest composition change in a forest-prairie ecotone. Forest Ecology and Management **261**:1833-1840.

Dorrough, J.W., J.E. Ash, S. Bruce, and S. McIntyre. 2007. From plant neighbourhood to landscape scales: how grazing modifies native and exotic plant species richness in grassland. Plant Ecology **191**:185-198.

Ewing, A.L., and D.M. Engle. 1988. Effects of late summer fire on tallgrass prairie microclimate and community composition. The American Midland Naturalist **120**:212-223.

Finney, M.A., and R.E. Martin. 1992. Calibration and field testing of passive flame height sensors. International Journal of Wildland Fire **2**:115-122.

Hadley, E.B. 1970. Net productivity and burning responses of native eastern North Dakota prairie communities. The American Midland Naturalist **84**:121-135.

Hadley, E.B., and R.P. Buccos. 1967. Plant community composition and net primary production within a native eastern North Dakota prairie. The American Midland Naturalist **77**:116-127.

Hovick, T.J., D.A. McGranahan, R.D. Elmore, J.R. Weir, and S.D. Fuhlendorf. 2017. Pyric-carnivory: Raptor use of prescribed fires. Ecology and Evolution **7**.

Hyde, K., M.B. Dickinson, G. Bohrer, D. Calkin, L. Evers, J. Gilbertson-Day, T. Nicolet, K. Ryan, and C. Tague. 2013. Research and development supporting risk-based wildfire effects prediction for fuels and fire management: status and needs. International Journal of Wildland Fire **22**:37-50.

Kolden, C.A. 2019. We're not doing enough prescribed fire in the western United States to mitigate wildfire risk. Fire **2**.

Krueger, E.S., T.E. Ochsner, D.M. Engle, J.D. Carlson, D. Twidwell, and S.D. Fuhlendorf. 2015. Soil moisture affects growing-season wildfire size in the southern Great Plains. Soil Physics and Hydrology:1567-1576.

LePage, Y., D. Oom, J.M.N. Silva, P. Jonsson, and J.M.C. Pereira. 2010. Seasonality of vegetation fires as modified by human action: observing the deviation from eco-climatic fire regimes. Global Ecology and Biogeography **19**:575-588.

Limb, R.F., T.J. Hovick, J.E. Norland, and J.M. Volk. 2018. Grassland plant community spatial patterns driven by herbivory intensity. Agriculture, Ecosystems and Environment **257**:113-119.

Marsden-Smedley, J.B., and W.R. Catchpole. 2001. Fire modelling in Tasmanian buttongrass moorlands. III. Dead fuel moisture. International Journal of Wildland Fire **10**:241-253.

McGranahan, D.A., D.M. Engle, S.D. Fuhlendorf, J.R. Miller, and D.M. Debinski. 2012. An invasive cool-season grass complicates prescribed fire management in a native warm-season grassland. Natural Areas Journal **32**:208-214.

Mell, W., M.A. Jenkins, J. Gould, and P. Cheney. 2007. A physics-based approach to modelling grassland fires. International Journal of Wildland Fire **16**:1-22.

Morgan, P., C.C. Hardy, T.W. Swetnam, M.G. Rollins, and D.G. Long. 2001. Mapping fire regimes across time and space: Understanding coarse and fine-scale fire patterns. International Journal of Wildland Fire **10**:329-342.

Morvan, D. 2013. Numerical study of the effect of fuel moisture content (FMC) upon the propagation of a surface fire on a flat terrain. Fire Safety Journal **58**:121-131.

Morvan, D., S. Meradji, and G. Accary. 2009. Physical modelling of fire spread in grasslands. Fire Safety Journal **44**:50-61.

Ohrtman, M.K., S.A. Clay, and A.J. Smart. 2015. Surface temperatures and durations associated with spring prescribed fires in South Dakota tallgrass prairies. American Midland Naturalist **173**:88-98.

Parisien, M.A., and M.A. Moritz. 2009. Environmental controls on the distribution of wildfire at multiple spatial scales. Ecological Monographs **79**:127-154.

Pausas, J.G., and J.E. Keeley. 2019. Wildfires as an ecosystem service. Frontiers in Ecology and the Environment **17**:289-295.

Quinn-Davidson, L.N., and J.M. Varner. 2012. Impediments to prescribed fire across agency, landscape and manager: an example from northern California. International Journal of Wildland Fire **21**.

Redman, R.E. 1972. Plant communities and soils of an eastern North Dakota prairie. Bulletin of the Torrey Botanical Club **99**:65-76.

Reinhardt, E.D., and M.B. Dickinson. 2010. First-order fire effects models for land management: Overview and issues. Fire Ecology **6**:131-142.

Reinhardt, E.D., R.E. Keane, and J.K. Brown. 2001. Modeling Fire Effects. International Journal of Wildland Fire **10**:373-380.

Ryan, K.C. 1981. Evaluation of a passive flame-height sensor to estimate forest fire intensity. Research Note PNW-390. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station.

Schultz, C.A., S.M. McCaffrey, and H.R. Huber-Stearns. 2019. Policy barriers and opportunities for prescribed fire application in the western United States. International Journal of Wildland Fire **28**:874-884.

Scott, J.H., and R.E. Burgan. 2005. Standard Fire Behavior Fuel Models: A comprehensive set for use with Rothermel's surface fire spread model. General Technical Report RMRS-GTR-153. USDA Forest Service, Rocky Mountain Research Station.

Simard, A., J. Eenigenburg, K. Adams, J. Roger Nissen, and A. Deacon. 1984. A general procedure for sampling and analyze wildland fire spread. Forest Science **30**:51-64.

Strong, D.J., A.C. Ganguli, and L.T. Vermeire. 2013. Fire effects on basal area, tiller production, and mortality of the C4 bunchgrass, Purple Threeawn. Fire Ecology **9**:89-99.

Trollope, W.S.W., L.A. Trollope, and D.C. Hartnett. 2002. Fire behaviour a key factor in the fire ecology of African grasslands and savannas.*in* International Conference on Forest Fire Research. Millpress, Luso, Coimbra, Portugal.

Twidwell, D., S.D. Fuhlendorf, J. Charles A. Taylor, and W.E. Rogers. 2013. Refining thresholds in couple fire-vegetation models to improve management of encroaching woody plants in grasslands. Journal of Applied Ecology **50**:603-613.

Verdu, F., J. Salas, and C. Vega-Garcia. 2012. A multivariate analysis of biophysical factors and forest fires in Spain, 1991-2005. International Journal of Wildland Fire **21**:498-509.

Weir, J.R. 2011. Are weather and tradition reducing our ability to conduct prescribed burns? Rangelands **33**:25-30.

Wragg, P.D., T. Mielke, and D. Tilman. 2017. Forbs, grasses, and grassland fire behaviour. Journal of Ecology:1-18.

Yoder, J., D. Engle, and S. Fuhlendorf. 2004. Liability, incentives, and prescribed fire for ecosystem management. Frontiers in Ecology and the Environment **2**:361-366.

Yurkonis, K.A., J. Dillon, D.A. McGranahan, D. Toledo, and B.J. Goodwin. 2019. Seasonality of prescribed fire weather windows and predicted fire behavior in the northern Great Plains, USA. Fire Ecology **15**.

Table 1. Summary of fuel conditions prior to fire ignitions, weather conditions during the fire events, and fire behavior responses for the 27 prescribed fire events sampled across three field stations in North Dakota from 2017 to 2019. We removed Oakville from the formal analysis. Due to incomplete datasets and a small sample size, we removed for the formal analyses both fires from Oakville, four fires from HREC (2017) and three from CGREC (2019).

		Station	
	Oakville	CGREC	HREC
Number of fires	2	15	10
Ignition Julian Day	157, 298	122 – 136	280 – 301
Fuel			
Fuel Density	1.65 – 2.95	0.47 – 1.55	0.34 – 2.42
Soil Moisture (%)	30.86 – 52.95	17.07 – 44.02	4.06 – 27.95
Fuel Moisture (%)	93.44 – 93.44	9.25 – 77.68	58.72 – 86.96
Fuel Load (g/m^2)	689.42 – 689.42	74.79 – 385.79	121.12 – 279.57
Weather			
Relative Humidity (%)	40.01 – 57.21	30.04 – 42.01	13.19 – 44.55
Air Temperature (°C)	9.74 – 26.33	16.22 – 22.14	4.68 – 24.67
Wind speed (kph)	10.52 – 12.05	12.78 – 19.56	5.19 – 19.94
Max. Wind Speed (kph)	15.86 – 26.52	25.10 – 33.27	15.23 – 30.86
Wind Direction (°)	157.00 – 0.40	39.71 – 322.40	180.81 – 289.05
Last Rain Event (days)	2 –13	4 – 8	2 – 31
Last Rain Event (cm)	1.78 – 2.51	0.20 – 0.48	0.20 – 0.56
Fire Behavior			
Max Temperature (°C)	239.56 – 328.24	52.67 – 395.27	90.49 – 324.44
Flame Height (cm)	47.04 – 47.04	0.93 – 96.56	19.44 – 71.11
ROS (m/s)	0.04 – 0.06	0.01 – 0.18	0.01 – 0.23
Direction (°)	190.35 – 209.24	98.24 – 263.12	105.47 – 216.90

Table 2. F-values from of Analysis of Variance test for fixed station effects on fire behavior responses summarized at the fire event scale.

	df	F	p
Maximum Temperature (°C)	2,24	0.62	0.5466
Flame Height (cm)	2,21	0.28	0.7622
Rate of Spread (m/s)	2,24	0.53	0.5972

Table 3. Best-performing additive models of fire behavior as explained by standardized fuel and weather variables from 18 prescribed fires conducted at CGREC and HREC in North Dakota from 2018 through 2019. Station was modeled as fixed effect, whereas Fire ID was modeled as a nested random effect. Chi-squared statistics and p-values are listed for the ANOVA test for difference between the top competing models for each fire response. Abbreviations and variables used are: *k*, the number of estimated parameters in the model; AICc, Akaike's information criterion, ΔAICc, the difference in AICc values in relation to the top model; AICc wt., weight of AICc score; Cum wt., cumulative weight of the AICc score; LL, Log-Likelihood; INT, intercept; FM, fuel moisture; DP, dew point; RH, relative humidity; WS, wind speed; LREQ, quantity of the last rain event.

Fire Behavior Metric	Model	*k*	AICc	ΔAICc	AICc Wt.	Cum. Wt.	LL	Chi-sq	*p*
Maximum Temperature	INT + FM + LREQ + RH	6	209.10	-	0.53	0.53	-94.73	6.45	0.01
	INT + FM + LREQ	5	210.91	1.81	0.21	0.74	-97.95		
Flame Height	INT + FM + LREQ + RH	6	166.56	-	0.70	0.70	-73.46	1.95	0.16
	INT + FM + LREQ + RH + DP	7	170.18	3.62	0.11	0.81	-72.49		
Rate of Spread	INT + WS + LREQ	5	54.43	-	0.33	0.33	-19.72	4.51	0.03
	INT + WS + LREQ + RH	6	54.56	0.13	0.31	0.64	-17.46		

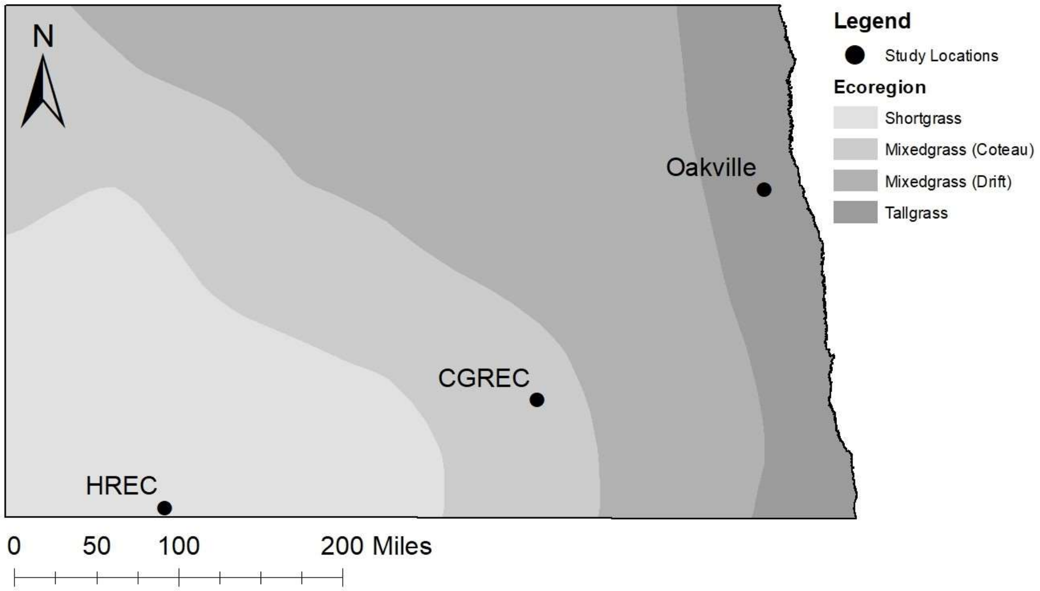

Figure 1. Map of field stations (study sites) across three ecoregions of North Dakota, USA.

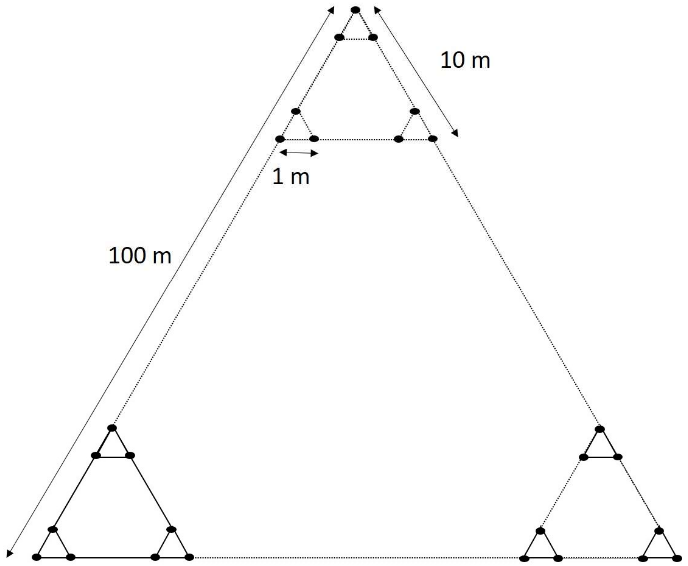

Figure 2. Sample points (black dots) were arranged into nested 1, 10, and 100 m sided triangles in a Sierpinski Triangle formation centered within a prescribed burn unit.

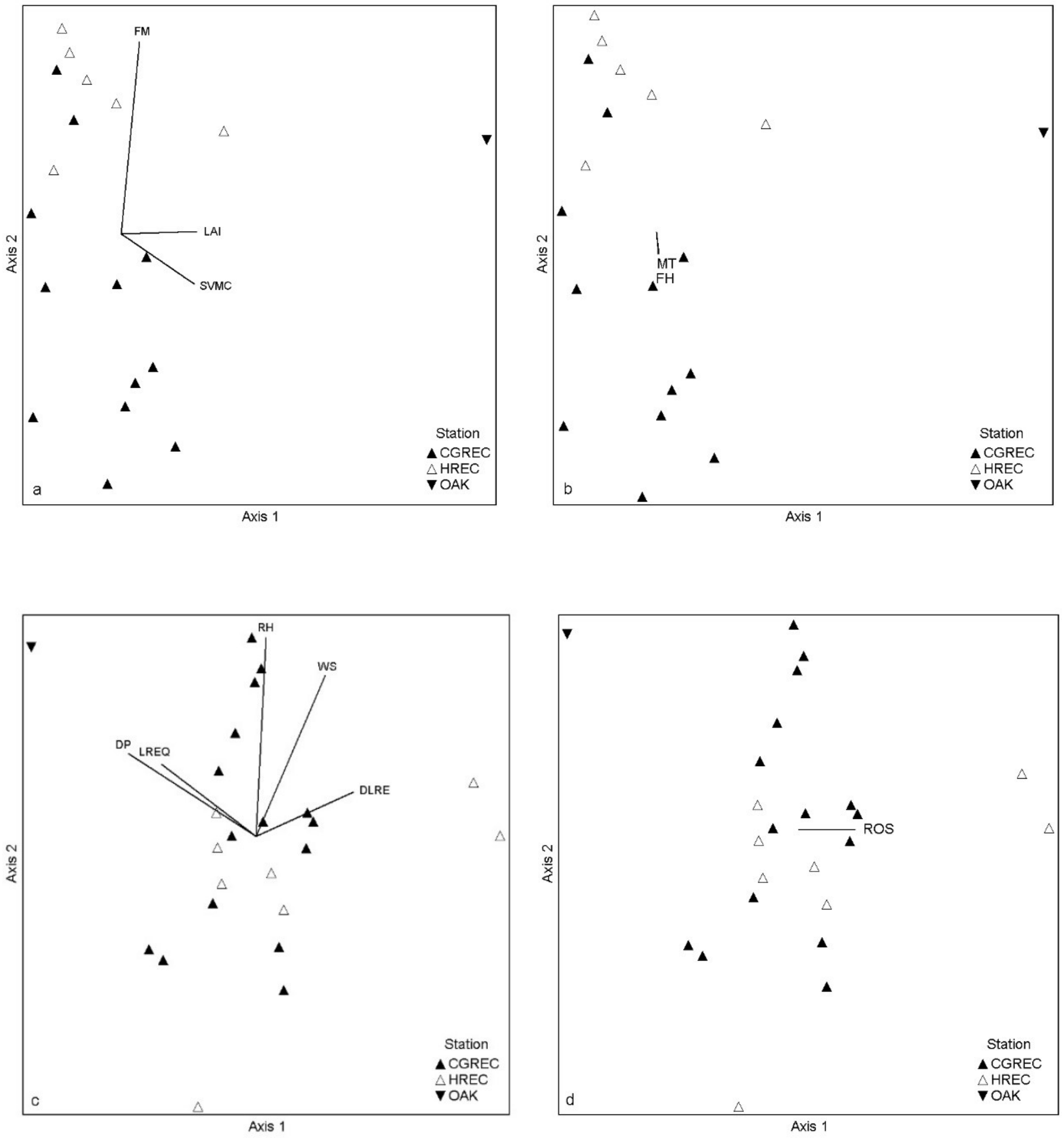

Figure 3. Principle Components Analysis of fuel (a and b) conditions prior to ignition and for weather (c and d) conditions during each fire event. Fuels were only analyzed for fire events with a complete fuel dataset (n = 19 of 27 possible fires). Weather was analyzed for fire events with a complete fire behavior dataset (n = 24 of 27 possible fires). Fire events are delineated by field station. Explanatory variables loadings with the main PCA axes are shown in panels (a) and (c) and the loadings of the fire behavior responses with the main axes are shown in panels (b) and

(d). Variables are abbreviated as follows: LAI, fuel load; SVMC, soil volumetric moisture content, FM, fuel moisture; DP, dew point; RH, relative humidity; WS, wind speed; DLRE, number of days since last rain event; LREQ, last rain event quantity.

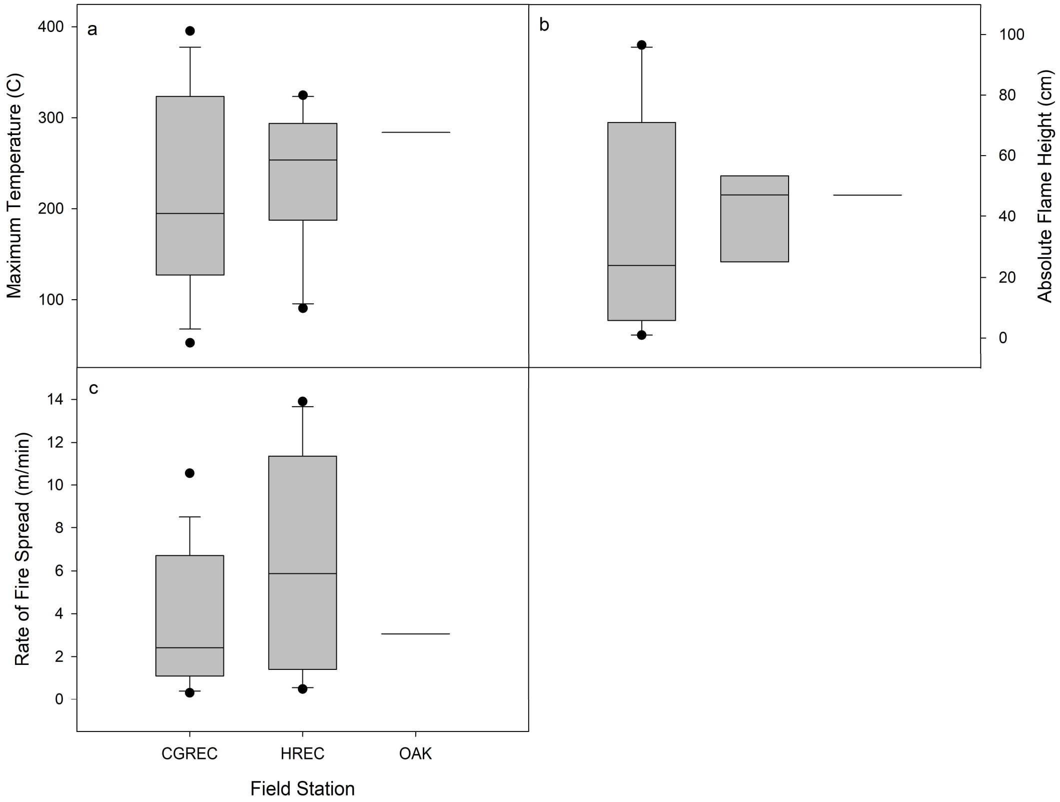

Figure 4. Boxplots of maximum temperature (a), flame height (b), and rate of fire spread (c, raw data) at fire event scale for all three sites.

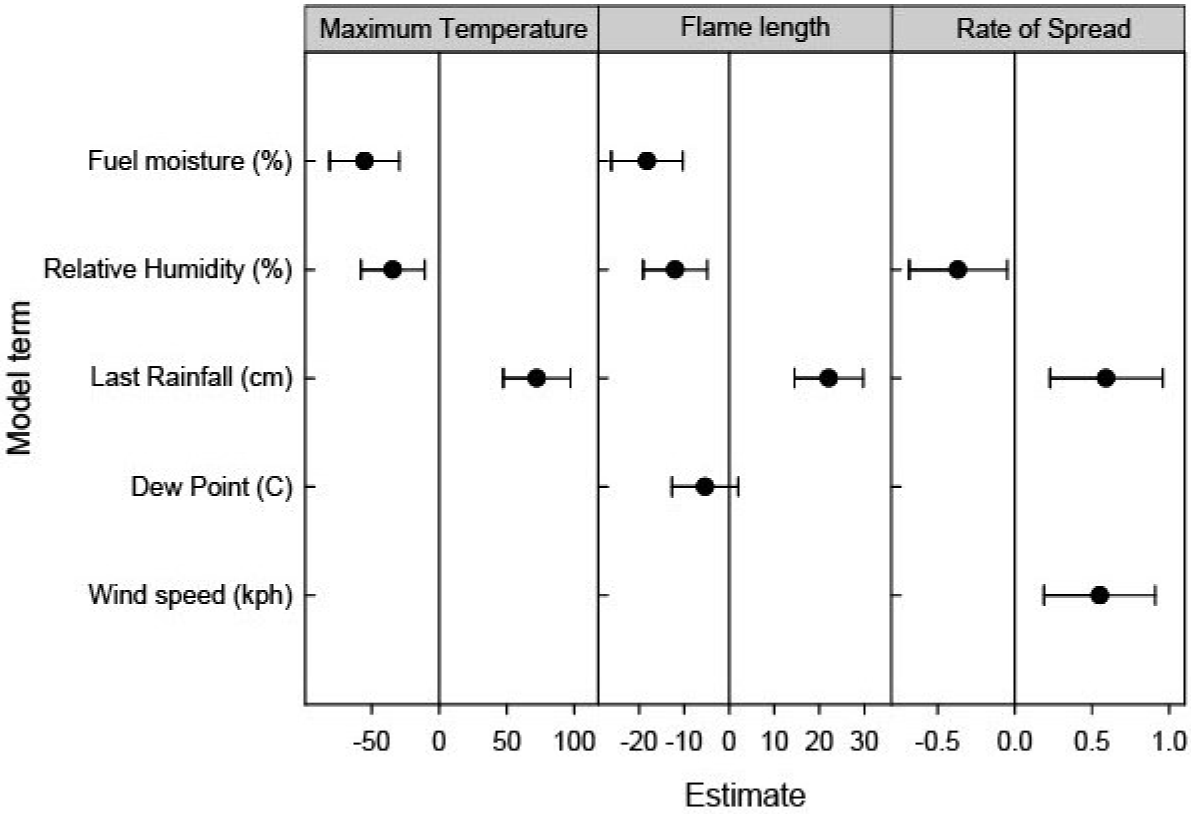

Figure 5. Parameter estimates and 95% confidence intervals (lower, upper) for fuel and weather terms averaged across all candidate models for maximum temperature, flame height, and rate of spread.

SPATIAL HETEROGENEITY OF FUELS AND FIRE BEHAVIOR IN NORTH DAKOTA GRASSLANDS

Abstract

The spatial heterogeneity of grassland fires may be linked to variation within the fuel bed. To quantify heterogeneity, we measured fuel bed properties (fuel load, soil and fuel moisture) prior to ignition and the resulting fire behavior (maximum temperature, flame height, and rate of fire spread) on 26 prescribed fires across North Dakota. We sampled 27 points on each fire arranged into a Sierpinski triangle sampling scheme with three fractally nested spatial scales. We used a hierarchical Restricted Maximum Likelihood (REML) variance component analysis with the full 27-point dataset to assess how each sample scale (100 m, 10 m , 1 m) contributed to the variance in the fuel and fire behavior responses. We then averaged Variance Component Estimates among all fires for each variable. Fuel loads (LAI) were most variable among the vertices of the 100 m and 10 m sample triangles and most similar at the 1 m scale. In contrast, fuel moisture was most variable at the 1 m sample triangle scale and the most similar at the 100 m scale. Soil moisture variance was not dependent on the sample scale. Assessing relationships between fuel explanatory and fire response variables, we found similar effects of heterogeneity in fuel load and fuel moisture on maximum temperature and flame height. We get the most variation in maximum temperature and flame height when fuel load is most consistent and when variation in fuel moisture is the greatest. Rate of spread has a limited dataset and did not relate to the variation in fuel load and fuel moisture. Understanding the spatial variability within the fuel bed and its contribution to fire behavior will aid fire practitioners to better predict the consequences of our fire management, guide future planning efforts, and provide a greater understanding of ecological fire effects.

Introduction

Grassland ecosystems rely on periodic disturbances such as fire and grazing to preserve biodiversity (Pausas and Keeley 2009). Disturbance promotes spatial and temporal variation in plant arrangement, structure, and composition (Collins and Smith 2006, Hovick et al. 2015). Grassland plants have evolved to withstand and promote the reoccurrence of fire through their structure and biochemical properties (Mitchell et al. 2009). Plants determine the structure, packing, and moisture content of the fuel bed for the next fire event (Gibson et al. 1990, Bidwell and Engle 1992, Keane 2016). Fuel beds, in turn, affect the flame front, local fire behavior, and, presumably, plant responses to the fire (Thaxton and Platt 2006, Loudermilk et al. 2009, Mitchell et al. 2009). The spatial pattern of fire behavior can interact with pre-existing fuel heterogeneity and affect the resulting heterogeneity of vegetation communities. Therefore, incorporating the ecology of fuels into fire management can critically link our understanding of feedbacks among fuels, fire behavior, and fire effects (Mitchell et al. 2009, Loudermilk et al. 2012).

For planning and suppression purposes, grasslands are often characterized as having a continuous fuel bed (Scott and Burgan 2005), but this is far from reality. The spatial organization of plants in a community is affected by soil resources (Faber and Markham 2011), species competition, and previous disturbance events (Gibson et al. 1990, Bidwell and Engle 1992). Plants are often spatially autocorrelated at fine-scales, and, as a result, fuel beds vary in continuity, load, and arrangement (Kennard and Outcalt 2006, Loudermilk et al. 2009, Wiggers et al. 2013). However, fine-scale fuel variability is often overlooked in coarse scale fire operations and modeling (Loudermilk et al. 2009), as most of the current probabilistic models assume continuous and homogenous fuel beds (Hargrove et al. 2000). Heterogeneous fuel data is often spatially averaged and homogenized for site scale fire behavior modeling (Vakili et al.

2016). Because the patchy distribution of fuel properties ultimately affects fire behavior through fuel availability and ignition probability, this heterogeneity should be considered when assessing the ecological effects of fire (Loudermilk et al. 2009, Parsons et al. 2011, Cawson and Duff 2019).

Fine-scale fuel heterogeneity is of growing interest in fire ecology and several methods exist to measure and quantify fuel beds. Direct methods include destructive biomass sampling (Brown 1981, Kidnie and Wotton 2015), planar transects of down woody fuels (Brown 1974), taking visual obstruction readings (Robel et al. 1970), using a falling-plate meter (Rayburn and Lozier 2003, Kidnie 2009), and measuring fuel height. Indirect methods include taking plot based estimates of plant percent cover and average height (Kennard and Outcalt 2006) and using a comparative approach with photographs of locations with known fuel loads and types (Burgan and Rothermel 1984). Remote sensing is also used to assess fuel loads at larger scales (Rollins et al. 2004, Lentile et al. 2006, McKenzie et al. 2007). Loudermilk et al. (2009) and Loudermilk et al. (2009) were among the first to use ground-based LIDAR to measure fuel bed architecture within a pine savanna understory. Each method has benefits and drawbacks. Sampling efforts can be labor intensive, time-consuming, not appropriate for all fuel types, too subjective, underestimate fuel load, or ignore critical plant architecture (Loudermilk et al. 2009, Kidnie and Wotton 2015). Therefore, we need a method to account for fine-scale fuels such as grasses without being too subjective.

Due to its ecological importance, there are growing efforts to quantify how fine-scale fuel heterogeneity contributes to heterogeneous patterns of fire behavior at different spatial scales (Loudermilk et al. 2009, Winter et al. 2012). The effects of fuels on fire behavior vary with the spatial and temporal scale of observation. The scale at which to quantify fuel and fire behavior heterogeneity is ultimately affected by the distribution and arrangement of the fuels, fuel load, structure, and connectivity (Loudermilk et al. 2014). Few studies have examined how pre-fire fuel heterogeneity will affect local fire behavior and therefore its effects (Twidwell et al. 2009, Wiggers et al. 2013). Fire ecologists within the longleaf pine ecosystem of the American southeast manipulated fine-scale (0.1–10 m) fuel loads to mimic the range of natural fuel loads. Fires in locations with greater fuel loads consumed more of the fuel bed and were more intense and more severe (Thaxton and Platt 2006, Gagnon et al. 2012). Ground-based LIDAR systems offer an indirect way to document fine-scale fuel heterogeneity. Using a fuel cell concept, Loudermilk et al. (2009) found that fuels were spatially independent at the sub-meter scale and that the two-dimensional heterogeneity of the fuel bed was responsible for a substantial proportion of the variation in the observed fire behavior.

Heterogeneous fire behavior affects the structure and function of ecological communities and promotes biodiverse conservation. Therefore, it is critical we characterize how fire behavior will respond to fuel heterogeneity when restoring degraded fire-dependent ecosystems. The conservation of species diversity in the face of non-native and woody invaders is a primary concern for grasslands of the northern Great Plains. Nonnative cool-season grasses decrease fuel bed heterogeneity through the spatial and temporal displacement of native plant communities (Gorgone-Barbosa et al. 2015), thus, creating produce larger and more uniform loads. Additionally, because most non-natives are cool season grasses, these species increase the moisture content of the fuel bed and the proportion of live fuel matter during historically key fire seasons in the Great Plains. This increased moisture content can detrimentally affect grassland fire behavior and result in lower fire intensity when fires are conducted within traditional spring and fall prescribed fire weather seasons (D'Antonio and Vitousek 1992, McGranahan et al. 2012, Livingston and Varner 2016).

As fire is returned to the landscape to restore fire-dependent ecosystems, there is an increasing need to bridge the knowledge gap between fuel heterogeneity and fire behavior, particularly in grassland plant communities. Quantifying fine-scale variability in the fuel bed arrangement will help fire managers and ecologists better understand mechanisms driving fine-scale fire behavior. Therefore, it is critical we characterize fuels and fire behavior over appropriate spatial scales to develop a fundamental understanding of fire behavior. To accomplish this, we examined the relationship between fuels and fire behavior over three nested spatial scales within three temperate grassland communities of North Dakota. We addressed the following questions:

1. Over what spatial scales are fuels and fire behavior most heterogeneous?
2. Does the heterogeneity within fuels contribute to the heterogeneity of fire behavior?

We hypothesized that fuels and fire behavior would be most heterogeneous at meter to sub-meter scales and that variation in fire behavior across 100 m to 1 m spatial scales would mirror the variation in fuels. Knowing how fuel heterogeneity affects fire behavior heterogeneity is critical for our assessment of ecological fire effects and has implications for the way we apply prescribed fire in grassland ecosystems.

Methods

Study sites

To quantify fuels and their associated fire behavior, we sampled 27 prescribed fires conducted on three university field stations across North Dakota, USA. These field stations, located in northeastern, central, and southwestern North Dakota, span a precipitation and vegetation composition gradient. Oakville Prairie, located in northeast North Dakota, (hereafter Oakville; centroid 47.902931, -97.315312; Emerado, ND, mean annual precipitation 55.1 cm) comprises 453-ha of remnant alkaline tallgrass prairie. Managed by the University of North Dakota and North Dakota Game and Fish, Oakville lies in the historic glacial lake plain of Lake Agassiz and exhibits minimal topographic variation (slope = 0 – 1 %). Silty-clay soils are of glaciolacustrine deposits distinctive to the Red River Valley. The fuel load is relatively high and homogenous because of a dense covering of herbaceous grasses and forbs (Hadley and Buccos 1967) and having received only sporadic defoliating disturbances after its inception in the 1940s (Hadley 1970, Redman 1972). In 2014, we divided the site into seven, 66 ha management units and incorporated rotational fall fires with a four-year return interval. There is no known history of grazing management on the site. For the purpose of this study, we sampled one fall (October) fire on Unit D (west half of section 16) in 2017 and one spring (June) fire in Unit F in 2019.

Central Grassland Research Extension Center, located in central North Dakota (hereafter CGREC, centroid 46.718686, -99.448521, Streeter, ND, mean annual precipitation 46.7 cm), is a 2158 ha site that includes agricultural fields, pastures, and 461 ha of remnant and improved mixed-grass prairie. Managed by North Dakota State University, CGREC lies within the Missouri Coteau ecoregion, which is characterized by undulating terrain (Bluemle 1991, Limb et al. 2018). Soils are well-drained, mildly alkaline loams with moderate clay content that are characteristic of glacial till deposits (USDA). Pasture Barker (259 ha, centroid 46.725796, -99.437877) has a 21 m elevation change across the entire pasture and a 3-12 m elevation change within burn units. Pasture Bob (259 ha, centroid 46.771358, -99.479609) has a 30 m north to south elevation change and varies 6-12 m in elevation within burn units. The pastures are dominated by herbaceous vegetation interspersed with dense aggregations of small shrubs (Limb et al. 2018, Lakey 2019). Fuel loads are in some instances discontinuous because of shallow rocky soils and cattle grazing activities. The current system of pyric herbivory management was initiated in 2017 after two years of applying smaller, experimental fires in each unit. Under this system, 8 to 16 ha prescribed fires are applied to 68 ha of each pasture in either spring or summer followed by grazing at a stocking rate of six acres per cow-calf pair. We sampled eight spring fires in May 2018 (four in pasture Bob, four in pasture Barker) and seven spring fires in May 2019 (four in pasture Bob, three in pasture Barker).

Hettinger Research Extension Center, located in southwestern North Dakota (hereafter HREC, site centroid 46.004443, -10.646477, Hettinger, ND, mean annual precipitation 38 cm), is a 457 ha site consisting of pastures enrolled in the Conservation Reserve Program (USDA NRCS). Managed by North Dakota State University, HREC is located in the Missouri Plateau ecoregion, which is characterized by rolling topography, gentle slopes, and level plains. The soils are loamy and formed from weathered bedrock and alluvium material (Aandahl 1982). HREC is divided into two pastures; both of which receive fire and grazing treatments. The Clements pasture (145 ha, centroid 45.80975, -102.62152) has a 19 m elevation change. The Fitch pasture (255 ha, centroid 46.039228, -102.720617) is relatively level has an 18 m elevation change. Herbaceous introduced species dominate both pastures (Spiess, pers comm May 2019). Pyric herbivory treatments were initiated in 2017, with cattle stocked at 25 cow-calf pairs/pasture and sheep stocked at 215 individuals per pasture. One quarter of each pasture receives at most a 16 ha prescribed fire after continuous grazing during the growing season. We sampled four fall fires in October 2017 (two from each pasture), four fires in October 2018 (two from each pasture), and two fires in October 2019 (one per pasture).

We burned all units with head or flanking fires during the early (May, June) or late (October) growing season in 2017, 2018, 2019 (Table 1). Fires were ignited 1 – 31 days following the last measurable rainfall. Fires at Oakville were conducted under two different burn bosses (W. Brown, Badger Creek Wildfire, Poplar, MT and B. Keller, Prairie Restorations, Inc, Moorhead, MN). Fires at CGREC and HREC were overseen by the same burn boss (D. McGranahan, NDSU Wildland Fire, Fargo, ND).

Data Collection

We quantified fuels and fire behavior heterogeneity (variance) at three spatial scales using a 27-point fractally nested triangular sampling scheme in the center of each fire unit (Figure 1). At the largest scale (100 m), we established an equilateral sampling triangle (4330.13 m^2) with vertices spaced 100 m apart. We then nested triangular subplots (43.3 m^2) with vertices spaced 10 m apart into each vertex of the 100 m sided triangle (3 – 10 m triangles = 1 – 100 m triangle). Finally, we nested an additional triangular subplot (0.43 m^2) with vertices spaced 1 m apart within the vertices of each 10 m sided triangle (3 – 1 m triangles = 1 – 10 m triangle). We then sampled fuel characteristics and fire behavior at the vertex of each of the resulting nine 1 m sided triangles (3 sample points × 3 - 1 m triangles × 3 - 10 m triangles = 27 sample points/100 m triangle).

Fuel conditions

We sampled the fuel bed at each sample point within 3 hours of fire ignition. We quantified fuel load as the overhead Leaf Area Index (LAI) at the soil surface (1 m long probe:

AccuPAR LP-80 ceptometer, Pullman, WA). Soil moisture was quantified by recording the soil Volumetric Water Content (VWC; Field Scout TDR-100, Aurora, IL) at each sample point. To quantify fuel moisture, we destructively collected all fuels above the soil surface within a 25 × 25 cm quadrat, positioned 0.5 m away from the sample point. We placed the fuel samples in airtight plastic bags to retain moisture. We measured the fuel wet mass, dried the fuels to a constant mass at 60°C for 48 hours, and then calculated the percent fuel moisture content with these values.

Fire Behavior

We quantified flame height and temperature associated with the fire front as it moved across each of the 27 sample points. We measured flame height using flame retardant strings suspended over each sample point with a metal stand modified after Ryan (1981) and Finney and Martin (1992). To prepare the strings, we soaked 16-ply 100% cotton string in a 1:1 solution of monoammonium phosphate for 24 hours and then dried them at 60°C for 24 hours. We suspended the strings vertically so that their lowest point was 15 cm above the soil surface and the upper point between 1 and 2 m above the soil surface with the final height determined based on the fuel load and height. After the fire event, we collected the strings and calculated the absolute flame height (Ryan 1981) by subtracting charred (visibly singed, *i.e.*, light brown color around string circumference) regions from the total string height.

To measure temperatures associated with the fire front, we positioned K-type thermocouples (Iconel, high temperature, fiber insulated, ungrounded, overbraided ceramic thermocouple, Omega, Norwalk, CT) 15 cm above the soil surface at each sample point. We used Arduino-based dataloggers to record the ambient temperature for each connected thermocouple (3 per datalogger) at 0.5 sec intervals for the duration of the fire event. Dataloggers were constructed from Adafruit components (Adafruit Industries, LLC, New York City, NY), housed within water-resistant Pelican cases (Pelican Products, Inc, Torrance, CA), and shielded from the fire front with metal duct covers. We queried the temperature logs for each thermocouple to determine the maximum temperature (ºC) recorded and its associated timestamp for each sample point. We used these values to calculate the direction (°) and rate of spread of the flame front (m/s) within the 1 m, 10 m, and 100 m triangles using equations 1 and 2 in (Simard et al. 1984). We omitted one fire (CGREC, May 2019, fire event 22) from the analysis in that did not carry well and failed to cross a majority (≥ 50%) of the sample points.

Data analysis

We assessed the station effect on fuels and fire behavior independently at each sampling scale for 26 fires at Oakville, CGREC, and HREC. First, we averaged values for all 27-sample points to generate the average fuel and fire behavior for each fire event (Fire event scale = 100 m triangle = 1 value/event). Second, we averaged values for the nine sample points within each vertex of the 100 m sample triangle (10 m triangle = 3 values/event). For the third dataset, we averaged values for the three sample points within each vertex of the three 10 m sample triangles (1 m triangle = 9 values/event). The final dataset contained the full 27-point dataset. We used nested ANOVA (PROC MIXED, Statistical Analysis Software, Cary, NC) to assess station effects on the fuel and fire behavior responses within each dataset following Dorrough et al. (2007). For these analyses, we included station as a fixed effect and scale appropriate nested random effects terms to account for the nested sampling design. For example, the full mixed model for the 27-point dataset included three random terms to account for each successive sampling scale 100 m (Station); 10 m (100 m, Station); 1m (10 m, 100 m, Station). We natural log transformed fuel load (LAI) and rate of fire spread and confirmed gaussian distribution for all response variables.

We used a hierarchical model to compute variance component estimates for all fuel and fire behavior metrics across all spatial scales. We used a Restricted Maximum Likelihood (REML) variance component analysis (PROC MIXED, Statistical Analysis Software, Cary, NC) with the full 27-point dataset to assess how each sample scale (10 m triangle, 1 m triangle, and sample point) contributed to the variance in the fuel and fire behavior responses following Dorrough et al. (2007). For this analysis, we used a single model with station as a fixed effect and three nested random effects terms to account for the nested sampling design. We computed variance component estimates for each fuel (fuel load, soil and fuel moisture) and fire behavior variable (maximum temperature, flame height, and rate of spread) for each fire with a likelihood ratio test by calculating the likelihood ratio statistic from the residual log likelihood of nested models (PROC MIXED, Statistical Analysis Software, Cary, NC). Due to the small sampling size at Oakville, we omitted Oakville from further analysis and treated it as a case study. Variance component estimates for each variable were then averaged across all fires from CGREC and HREC. To examine if the variation in fuels contributes to the variation in fire behavior at several spatial scales, we used a Kendall rank correlation on the average fuel variance component against the average fire behavior variance component (Table 3, Figure 2).

Results

Fuel loads (LAI) were most variable among the vertices of the 100 m and 10 m sample triangles and most similar at the 1 m scale. In contrast, fuel moisture was most variable at the 1m sample triangle scale and the most similar at the 100 m scale. Variance in soil moisture was not dependent on the sample scale. Sampling scale affects maximum temperature and flame height in that temperatures were more variable at the 1 m than at the 10 m scale. Variance in rate of spread was indistinguishable among the scales sampled.

When looking at the relationships between fuel and fire response variables, we find that the effects of heterogeneity in fuel load and fuel moisture on maximum temperature and flame height are similar. When fuel load is the most consistent, we get the most variation in maximum temperature and flame height. A positive relationship exists between fuel moisture and maximum temperature and flame height in that when variation is the greatest in fuel moisture, we get the greatest variation in maximum temperature and flame height. This is less clear for soil moisture, but the pattern of effects on variance is consistent between maximum temperature and flame height. Rate of spread is a more limited dataset and in this case variation in fuel load and fuel moisture, albeit at a large scale, did not relate to variation in rate of spread. Of the Kendall rank correlation, we found fuel variance components were not correlated with variance of fire behavior.

Discussion

Spatially heterogeneous prescribed fires can positively affect heterogeneity and subsequent biodiversity in grassland communities. To better understand the mechanisms driving heterogeneous fire behavior, and therefore the resulting ecological effects, we need fine-scale observations of pre-fire fuel beds and patterns of fire behavior (Hiers et al. 2020). However, fuel beds and the resulting fire behavior are not often examined at such fine, or even several spatial scales. This misses a critical opportunity to identify ecologically relevant effects and develop a greater understanding of the contributions of the fuel bed to fire behavior. Having collected data within pyric herbivory managed systems, we hypothesized fuel bed properties, and therefore the resulting fire behavior, would exhibit higher variance (heterogeneity) at finer scales. This would meet the assumption that there was an inverse linear relationship between heterogeneity and scale, as identified by Wiens (1989), where heterogeneity decreases as the scale of observation increases. Winter et al. (2012) found this relationship to be supported for vegetation height and visual obstruction in pyric herbivory managed *Artemisia filifolia* shrublands of the southern Great Plains. However, only fuel moisture met the inverse linear assumption, as variance decreased with increasing scale. Our results imply that the highest heterogeneity occurs at the patch scale. Where most fuel metrics were heterogeneous at larger scales (100 m), fuel moisture and fire behavior were most variable at the finest scale of observation (1 m). Maximum temperature, flame height, and soil moisture variances were most variable at intermediate scales.

We related properties of the fuel bed at the time of ignition to the observed fire behavior and found the spatial heterogeneity within fuels failed to reflect heterogeneity of the resulting fire behavior. Fuels are a product of spatially and temporally dynamic plant communities. The spatial and temporal heterogeneity of plant composition and arrangement result from resource allocation, competition, and interactions with disturbances from grazing and fire (Faber and Markham 2011). Additionally, local fertilization events in grazed grasslands can contribute to increased fine-scale variation in plant productivity and subsequent contributions to fuel load. In the presence of these processes, we found fuel load was most homogenous at fine scales. Having measured fuel load with 1 m long probe, it is logical the variance was not high at the 1 m scale because the measurement inherently integrated fuel heterogeneity over that distance. Despite the variance of fuel load (or lack thereof) at finer scales, prescribed fire practitioners can increase the output energy by manipulating ignition patterns and shapes (Cheney and Gould 1995, Hiers et al. 2020). However, temporal variability (e.g., phenology, fuel moisture) within the fuel bed can diminish such energy and produce spatially heterogeneous fire behavior. Soil moisture, previously correlated with fuel moisture (Krueger et al. 2016), is a function of soil properties and reflects the variation in soil types within a site, rather than overall burn unit. Therefore, the variance in soil moisture may be affected by size and topography of the burn unit.

Overall, these findings reflect Keane (2016) who reported that fine fuels are more spatially uniform than coarser fuels such as woody debris. Other previous work used various techniques to assess fuel and fire behavior heterogeneity. Loudermilk et al. (2014) used high-resolution infrared thermal imagery to identify a scale of 33 × 33 cm that could relate heterogeneous fuels to heterogeneous fire behavior for southern longleaf pine forests. However, a scale of 1 cm^2 was critical to identify heterogeneity within the fuel bed. Hiers et al. (2009) employed LIDAR to examined wildland fuel cells. They determined 4 × 4 m cells became spatially independent at scales beyond 0.5 m^2. They also found fuel cell type and spatial distribution to effect fire behavior.

From the previous chapter, we learned weather is the predominant driver of fire behavior. Maximum temperature and flame height were driven by fuel moisture, quantity of last rain event, and relative humidity. Future work should also consider how thermodynamics affect the spatial variation of fire behavior in prescribed fires of grassland communities. Lacking an overstory canopy, grasslands are highly responsive to changes in weather conditions. Changes in wind speed, direction (Linn and Cunningham 2005), or relative humidity (Kennard and Outcalt 2006) can be responsible for the spatial variability seen in fire behavior. Higher wind speeds can override the effect of moisture content on the rate of spread (Cheney et al. 1993, Cruz et al. 2018). Because managers of the northern Great Plains preferentially ignite prescribed fires in the spring, they need to recognize how live fuels and increased fuels moisture of the lower fuel bed will affect fire behavior under all acceptable wind speeds.

Overall, our analysis failed to link fuel bed heterogeneity with heterogeneity in the observed fire behavior. We intend to perform a mantel test following the analysis outlined in Deal (2016) with distance matrices based on the full 27 point dataset to assess pairwise fuel-fire relationships with corrections for the physical relationships among sample points to test over what fuel response distances the fire behavior responses are correlated. To better predict the consequences of our fire management, we need to understand factors affecting variable fire behavior (Mitchell et al. 2009, Loudermilk et al. 2014). Acknowledging the spatial variability within the fuel bed and its contribution to fire behavior will guide future planning efforts, monitoring of treatment efficacy, greater understanding of fire effects, and risk assessment (Parresol et al. 2012).

Acknowledgements

Personnel from Badger Creek Wildfire (Poplar, MT), Prairie Restorations, Inc, (Moorhead, MN), NDSU Wildland Fire (Fargo, ND), and the North Dakota Agricultural Experiment station assisted with prescribed fire preparation, planning, and operations. L. LaFond, C. LaFond, and E. Wahl assisted with datalogger assembly. M. Lakey, J. Spiess, J. Cutter, and A. Steele assisted with sensor deployment and data collection. Funding for components and materials was made available through the Biology Departmental Research

Committee. Funding to attend and present at conferences was awarded through the departmental Academic Programs and Student Awards Committee (APSAC) Research Stipend. Lastly, many thanks to B. Darby, who endlessly answers all my statistics and modeling questions.

Literature Citations

Aandahl, A.R. 1982. Soils of the Great Plains: land use, crops, and grasses, Lincoln, NE.

Bidwell, T.G., and D.M. Engle. 1992. Relationship of fire behavior to tallgrass prairie herbage production. Journal of Rangeland Management **45**:579-584.

Bluemle, J.P. 1991. The Face of North Dakota. Revised edition. Bismarck Educational Series 21, ND, USA.

Brown, J.K. 1974. Handbook for Inventorying Downed Woody Material. General Technical Report INT-16. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Brown, J.K. 1981. Bulk Densities of Nonuniform Surface Fuels and Their Application to Fire Modeling. Forest Science **27**:667-683.

Burgan, R.E., and R.C. Rothermel. 1984. BEHAVE: Fire behavior prediction and fuel modeling system -- FUEL subsystem. PMS 439-1. National Wildfire Coordinating Group.

Cawson, J.G., and T.J. Duff. 2019. Forest fuel bed ignitability under marginal fire weather conditions in Eucalyptus forests. International Journal of Wildland Fire **28**:198-204.

Cheney, N.P., and J.S. Gould. 1995. Fire growth in grasslands. International Journal of Wildland Fire **5**:237-247.

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

Collins, S., and M. Smith. 2006. Scale-dependent interaction of fire and grazing on community heterogeneity in tallgrass prairie. Ecology **87**:2058-2067.

Cruz, M.G., A.L. Sullivan, J.S. Gould, R.J. Hurley, and M.P. Plucinski. 2018. Got to burn to learn: the effect of fuel load on grassland fire behaviour and its management implications. International Journal of Wildland Fire **27**:727-741.

D'Antonio, C.M., and P.M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics **23**:63-87.

Deal, B.W. 2016. Plant and arthropod associations with environmental gradients in a northern tallgrass prairie. Master of Science. University of North Dakota, Grand Forks, ND.

Dorrough, J.W., J.E. Ash, S. Bruce, and S. McIntyre. 2007. From plant neighbourhood to landscape scales: how grazing modifies native and exotic plant species richness in grassland. Plant Ecology **191**:185-198.

Faber, S., and J. Markham. 2011. Temporal and spatial dynamics in a northern tallgrass prairie. Plant Ecology **212**:1577-1588.

Finney, M.A., and R.E. Martin. 1992. Calibration and field testing of passive flame height sensors. International Journal of Wildland Fire **2**:115-122.

Gagnon, P.R., K.E. Harms, W.J. Platt, H.A. Passmore, and J.A. Myers. 2012. Small-scale variation in fuel loads differentially affects two co-dominant bunchgrasses a species-rich pine savanna. PLOS One **7**.

Gibson, D.J., D.C. Hartnett, and G.L. Merrill. 1990. Fire temperature heterogeneity in contrasting fire prone habitats: Kansas tallgrass prairie and Florida sandhill. Bulletin of the Torrey Botanical Club **117**:349-356.

Gorgone-Barbosa, E., V.R. Pivello, S. Bautista, T. Zupo, M.N. Rissi, and A. Fidelis. 2015. How can an invasive grass affect fire behavior in a tropical savanna? A community and individual plant level approach. Biological Invasions **17**:423-431.

Hadley, E.B. 1970. Net productivity and burning responses of native eastern North Dakota prairie communities. The American Midland Naturalist **84**:121-135.

Hadley, E.B., and R.P. Buccos. 1967. Plant community composition and net primary production within a native eastern North Dakota prairie. The American Midland Naturalist **77**:116-127.

Hargrove, W.W., R.H. Gardner, M.G. Turner, W.H. Romme, and D.G. Despain. 2000. Simulating fire patterns in heterogeneous landscapes. Ecological Modeling **135**:243-263.

Hiers, J.K., J.J. O'Brien, R. Mitchell, J.M. Grego, and E.L. Loudermilk. 2009. The wildland fuel cell concept: an approach to characterize fine-scale variation in fuels and fire in frequently burned longleaf pine forests. International Journal of Wildland Fire **18**:315-325.

Hiers, J.K., J.J. O'Brien, J.M. Varner, B.W. Butler, M. Dickinson, J. Furman, M. Gallagher, D. Godwin, S.L. Goodrick, S.M. Hood, A. Hudak, L.N. Kobziar, R. Linn, E.L. Loudermilk, S. McCaffrey, K. Robertson, E.M. Rowell, N. Skowronski, A.C. Watts, and K.M. Yedinak. 2020. Prescribed fire science: the case for a refined research agenda. Fire Ecology **16**.

Hovick, T.J., D. Elmore, S.D. Fuhlendorf, D.M. Engle, and R.G. Hamilton. 2015. Spatial heterogeneity increases diversity and stability in grassland bird communities. Ecological Applications **25**:662-672.

Keane, R.E. 2016. Spatiotemporal variability of wildland fuels in US northern Rocky Mountain forests. Forests **7**.

Kennard, D.K., and K. Outcalt. 2006. Modeling spatial patterns of fuels and fire behavior in a longleaf pine forest in the southeastern USA. Fire Ecology **2**:31-52.

Kidnie, S., and B.M. Wotton. 2015. Characterisation of the fuel and fire environment in southern Ontario's tallgrass prairie. International Journal of Wildland Fire **24**:1118-1128.

Kidnie, S.M. 2009. Fuel load and fire behaviour in the southern Ontario tallgrass prairie. Master of Science. University of Toronto, Toronto, Ontario, CA.

Krueger, E.S., T.E. Ochsner, J.D. Carlson, D.M. Engle, D. Twidwell, and S.D. Fuhlendorf. 2016. Concurrent and antecedent soil moisture relate positively or negatively to probability of large wildfires depending on season. International Journal of Wildland Fire **25**:657-668.

Lakey, M. 2019. Pages Dominant plant community at Central Grasslands Research Extension Center, NDSU, Streeter, ND.

Lentile, L.B., Z.A. Holden, A.M. Smith, M.J. Falkowski, A.T. Hudak, P. Morgan, S.A. Lewis, P.E. Gessler, and N.C. Benson. 2006. Remote sensing techniques to assess active fire characteristics and post-fire effects. International Journal of Wildland Fire **15**:319-345.

Limb, R.F., T.J. Hovick, J.E. Norland, and J.M. Volk. 2018. Grassland plant community spatial patterns driven by herbivory intensity. Agriculture, Ecosystems and Environment **257**:113-119.

Linn, R.R., and P. Cunningham. 2005. Numerical simulations of grass fires using a coupled atmosphere-fire model: Basic fire behavior and dependence on wind speed. Journal of Geophysical Research **110**.

Livingston, A.C., and J.M. Varner. 2016. Fuel moisture differences in a mixed native and non-native grassland: implications for fire regimes. Fire Ecology **12**:73-87.

Loudermilk, E.L., G.L. Achtemeier, J.J. O'Brien, J.K. Hiers, and B.S. Hornsby. 2014. High-resolution observations of combustion in heterogenous surface fuels. International Journal of Wildland Fire **23**:1016-1026.

Loudermilk, E.L., J.K. Hiers, J.J. O'Brien, R.J. Mitchell, A. Singhania, J.C. Fernandez, W.P.C. Jr, and K.C. Slatton. 2009. Ground-based LIDAR: a novel approach to quantify fine-scale fuelbed characteristics. International Journal of Wildland Fire **18**:676-685.

Loudermilk, E.L., J.J. O'Brien, R.J. Mitchell, W.P.C. Jr, J.K. Hiers, S. Grunwald, J. Grego, and J.C. Fernandez-Diaz. 2012. Linking complex forest fuel structure and fire behavior at fine scales. International Journal of Wildland Fire **21**:882-893.

McGranahan, D.A., D.M. Engle, S.D. Fuhlendorf, J.R. Miller, and D.M. Debinski. 2012. An invasive cool-season grass complicates prescribed fire management in a native warm-season grassland. Natural Areas Journal **32**:208-214.

McKenzie, D., C.L. Raymond, L.K.B. Kellogg, R.A. Norhelm, A.G. Andreu, A.C. Bayard, K.E. Koppper, and E. Elman. 2007. Mapping fuels at multiple scales: landscape application of the Fuel Characteristic Classification System. Canadian Journal of Forest Research **37**:2421-2437.

Mitchell, R.J., J.K. Kiers, J. O'Brien, and G. Starr. 2009. Ecological forestry in the southeast: understanding the ecology of fuels. Journal of Forestry:391-397.

Parresol, B.R., J.H. Scott, A. Andreu, S. Prichard, and L. Kurth. 2012. Developing custom fire behavior fuel models from ecologically complex fuel structures for upper Atlantic Coastal Plain forests. Forest Ecology and Management **273**:50-57.

Parsons, R.A., W.E. Mell, and P. McCauley. 2011. Linking 3D spatial models of fuels and fire: effects of spatial heterogeneity on fire behavior. Ecological Modeling **222**:679-691.

Pausas, J.G., and J.E. Keeley. 2009. A burning story: the role of fire in the history of life. BioScience **59**:593-601.

Rayburn, E., and J. Lozier. 2003. A falling plate meter for estimating pasture forage mass. West Virginia University Extension Service.

Redman, R.E. 1972. Plant communities and soils of an eastern North Dakota prairie. Bulletin of the Torrey Botanical Club **99**:65-76.

Robel, R.J., J.T. Briggs, A.D. Dayton, and L.C. Hulbert. 1970. Relationships between visual obstruction measurements and weight of grassland vegetation. Journal of Rangeland Management **23**:295-297.

Rollins, M.G., R.E. Keane, and R.A. Parsons. 2004. Mapping fuels and fire regimes using remote sensing, ecosystem simulation, and gradient modeling. Ecological Applications **14**:75-95.

Ryan, K.C. 1981. Evaluation of a passive flame-height sensor to estimate forest fire intensity. Research Note PNW-390. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station.

Scott, J.H., and R.E. Burgan. 2005. Standard Fire Behavior Fuel Models: A comprehensive set for use with Rothermel's surface fire spread model. General Technical Report RMRS-GTR-153. USDA Forest Service, Rocky Mountain Research Station.

Simard, A.J., J.E. Eenigenburg, K.B. Adams, J. Roger L. Nissen, and A.G. Deacon. 1984. A general procedure for sampling and analyzing wildland fire spread. Forest Science **30**:51-64.

Thaxton, J.M., and W.J. Platt. 2006. Small-scale fuel variation alters fire intensity and shrub abundance in pine savanna. Ecology **87**:1331-1337.

Twidwell, D., S.D. Fuhlendorf, D.M. Engle, and J. Charles A. Taylor. 2009. Surface fuel sampling strategies: linking fuel measurements and fire effects. Rangeland Ecology and Management **62**:223-229.

Vakili, E., C.M. Hoffman, R.E. Keane, W.T. Tinkham, and Y. Dickinson. 2016. Spatial variability of surface fuels in treated and untreated ponderosa pine forests of the southern Rocky Mountains. International Journal of Wildland Fire **25**:1156-1168.

Wiens, J.A. 1989. Spatial Scaling in Ecology. Functional Ecology **3**:385-397.

Wiggers, M.S., L.K. Kirkman, R.S. Boyd, and J.K. Hiers. 2013. Fine-scale variation in surface fire environment and legume germination in the longleaf pine ecosystem. Forest Ecology and Management **310**:54-63.

Winter, S.L., S.D. Fuhlendorf, C.L. Goad, C.A. Davis, K.R. Hickman, and J. David M Leslie. 2012. Restoration of fire-grazing interaction in Artemesia filifolia shrubland. Journal of Applied Ecology **49**:242-250.

Table 1. Summary of weather conditions during the 26 prescribed fire events sampled across three field stations in North Dakota from 2017 to 2019. Oakville fires were removed from average variance component estimation due to small sample sizes and thus is treated as a case study.

	Station		
	Oakville	CGREC	HREC
Number of fires	2	15	10
Ignition Julian Day	157, 298	122 – 136	280 – 301
Weather			
Relative Humidity (%)	40.01 – 57.21	30.04 – 42.01	13.19 – 44.55
Air Temperature (°C)	9.74 – 26.33	16.22 – 22.14	4.68 – 24.67
Wind speed (kph)	10.52 – 12.05	12.78 – 19.56	5.19 – 19.94
Max. Wind Speed (kph)	15.86 – 26.52	25.10 – 33.27	15.23 – 30.86
Wind Direction (°)	157.00 – 0.40	39.71 – 322.40	180.81 – 289.05
Last Rain Event (days)	2 –13	4 – 8	2 – 31
Last Rain Event (cm)	1.78 – 2.51	0.20 – 0.48	0.20 – 0.56

Table 2. F-values associated with fixed station effect for models of fuels and fire behavior (maximum temperature, rate of spread, and flame height) summarized and assessed independently at four spatial scales. Parameter significance are denoted as *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.0001$.

	df	Fire event	10 m	1 m	Sample point
Fuel Load (LAI)	2,20	7.48**	7.44**	7.53**	7.57**
Soil Moisture (%)	2,23	11.68**	11.72**	11.67**	11.70**
Fuel Moisture (%)	2,18	13.47**	13.49**	13.85**	13.45**
Maximum Temperature (°C)	2,23	0.42	0.44	0.43	0.42
Flame Height (cm)	2,20	0.15	0.15	0.15	0.15
(ln)Rate of Spread (m/s)	2,23	0.88	1.28	0.58	–

Table 3. Correlations associated with fuel bed variance (fuel load, fuel moisture, soil moisture) against fire behavior variance (maximum temperature, flame height, rate of spread). Rate of spread variance had a standard deviation of zero, and thus no correlation performed.

	Maximum Temperature	Flame Height	Rate of Spread
Fuel Load	-0.0925	-0.1899	-0.1370
Soil Moisture	0.0136	-0.1662	0.0895
Fuel Moisture	0.1339	0.1446	-0.0669

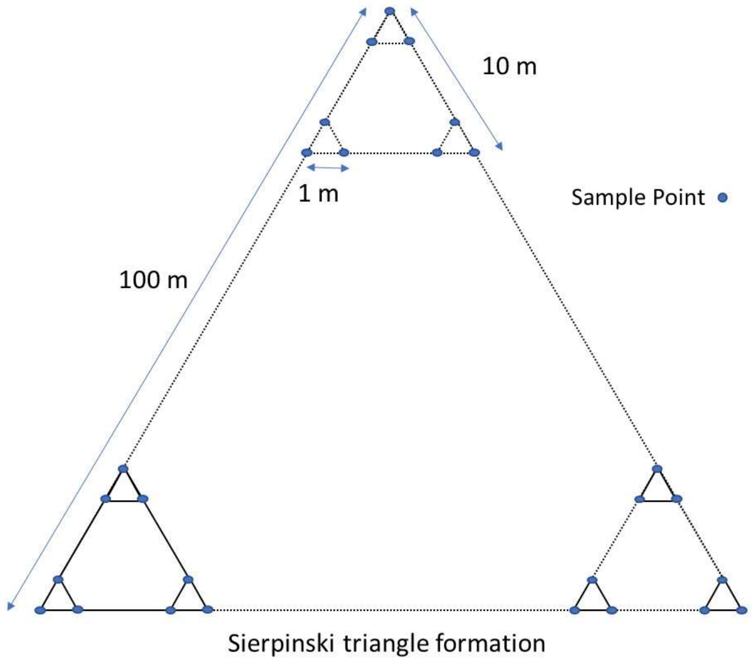

Figure 1. Sample points were arranged into a nested 1, 10, and 100 m sided equilateral triangles (Sierpinski triangle formation) within the center of each fire unit. We assessed fuels and fire behavior at 27 sample points within each fire.

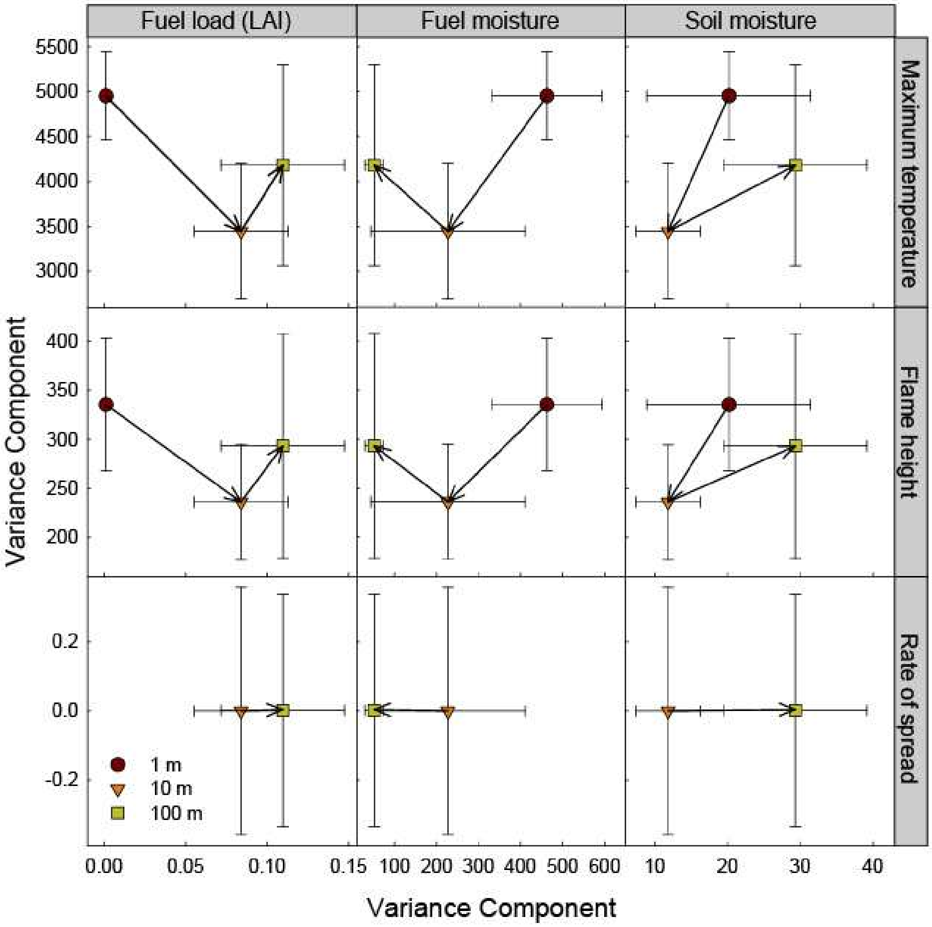

Figure 2. Estimates (± SE) of the contribution of nested variance components to the variance in fuels against fire behavior fuel load (a), % fuel moisture (b), and % soil moisture (c). Variance components were estimated using REML models and assess the contribution of differences among groups of sample points spaced 100 m apart in each fire event, among groups of sample points spaced 10 m in each fire event, and among sample points spaced 1 m apart to variance in the fuel and fire behavior responses.

CONCLUSIONS

Grasslands are one of many disturbance-dependent ecosystems that rely on periodic fire to support and maintain biodiversity. Natural resource managers within the Great Plains employ seasonal and frequent prescribed fire to promote species diversity, suppress nonnative species or woody shrub encroachment, and increase quantity of biomass for foraging animals (Coppedge et al. 2008, Engle et al. 2008). Often, fuel and fire behavior data from the central Great Plains are used to inform modeling applications, fire planning and suppression efforts in the northern Great Plains. Although similar in structure and function, species comprising the fuelbed of the northern Great Plains substantially varies from that in the central Great Plains and can have implications on the resulting fire behavior. To address the local knowledge gap, we quantitatively evaluated fuelbed properties, weather conditions, and fire behavior of 27 prescribed fires across three northern grassland ecoregions of North Dakota.

In Chapter One, we addressed how properties of the fuelbed and weather conditions at the time of a burn would contribute to fire behavior. We sampled at three field stations across North Dakota yet found no evidence of station effect. This would imply we applied prescribed fires under similar fuel and weather conditions despite burning across spring and fall seasons. It would also suggest burn managers are seeking preferential weather windows to generate specific fire behavior that will carry across the fuelbed and meet treatment objectives. We found weather variables to be the strongest explanation driving fire behavior. Wind direction was found to be the primary significant explanatory variable for maximum temperature and flame heights yielded by fire events. Rate of fire spread was best explained by station, fuel moisture, relative humidity, wind speed, and days since the previous rain event.

In Chapter Two, we assessed the spatial heterogeneity of the fuelbed, which could potentially generate heterogeneous fire behavior. Through a nested sampling scheme (Sierpinski Triangle), we evaluated four levels of magnitude (Fire event, 100 m, 10m, and 1 m). We found more variance (heterogeneity) within the biomass of the fuelbed (fuel load, g/m2) and fuel moisture (%) at the finest (1 m) scale. However, this variation was lost at the next successive scales (10 m). Soil moisture and plant density were most heterogeneous at the fire event scale. The heterogeneity within fuel load and moisture did not correlate to fire behavior. All metrics of fire behavior (maximum temperature (°C), flame height (cm), and rate of spread (m/s)) were most heterogeneous at the fire event scale.

To further progress in our understanding of fire behavior in the northern Great Plains, we should continue to quantitatively assess pre-fire fuel bed conditions with the observed fire behavior. This work should be expanded to encompass other agencies who use prescribed fire in their grassland management. While providing replication across different ecoregions, it would also offer insight to human agency and decision factors regarding fuel and weather conditions across agencies. We should further assess different ignition techniques and strategies to manipulate the geometry of the flame front to generate variable fireline intensity and rate of spread (Cheney and Gould 1997). Appropriate metrics should be collected to calculate and predict fireline intensity, to then be compared with actual outcomes. To assess the severity and efficacy of our fires, we should establish pre- and post-fire monitoring protocols that reflect the fire behavior sampling scheme (Morgan et al. 2001, Batllori et al. 2015). To round out the ecology of fuels, we should consider functional group, species identity, plant height, and their architecture and their contribution to the fuel bed (Loudermilk et al. 2009, Mitchell et al. 2009, Loudermilk et al. 2012).

The combined results of this work can be used to guide fire managers in the northern Great Plains. Fire managers and ecologists need to assess what generates patchiness and the consequences it may have for management. As we burned under similar fuels and weather conditions, our current practices generated similar fire behavior across the state. This would suggest that to generate variable fire behavior, we need to ignite prescribed fires primarily under different weather conditions by altering the seasonal timing or frequency of returned fire events. By understanding the fire behavior generated under local fuel and weather conditions rather than extrapolations, we are more likely to achieve our ecological and managerial objectives.

Literature Citations

Batllori, E., D.D. Ackerly, and M.A. Moritz. 2015. A minimal model of fire-vegetation feedbacks and disturbance stochasticity generates alternative stable states in grassland-shrubland-woodland systems. Environmental Research Letters **10**.

Cheney, N.P., and J.S. Gould. 1997. Fire Growth and Acceleration. International Journal of Wildland Fire **7**:1-5.

Coppedge, B.R., S.D. Fuhlendorf, W.C. Harrell, and D.M. Engle. 2008. Avian community response to vegetation and structural features in grasslands managed with fire and grazing. Science Direct **141**:1196-1203.

Engle, D.M., S.D. Fuhlendorf, A. Roper, and J. David M. Leslie. 2008. Invertebrate community response to a shifting mosaic of habitat. Rangeland Ecology Management **61**:55-62.

Loudermilk, E.L., J.K. Hiers, J.J. O'Brien, R.J. Mitchell, A. Singhania, J.C. Fernandez, W.P.C. Jr, and K.C. Slatton. 2009. Ground-based LIDAR: a novel approach to quantify fine-scale fuelbed characteristics. International Journal of Wildland Fire **18**:676-685.

Loudermilk, E.L., J.J. O'Brien, R.J. Mitchell, J. Wendell P. Cropper, J.K. Hiers, S. Grunwald, J. Grego, and J.C. Fernandez-Diaz. 2012. Linking complex forest fuel structure and fire behaviour at fine scales. International Journal of Wildland Fire **21**:882-893.

Mitchell, R.J., J.K. Hiers, J. O'Brien, and G. Starr. 2009. Ecological forestry in the Southeast: Understanding the ecology of fuels. Forest Ecology:391-397.

Morgan, P., C.C. Hardy, T.W. Swetnam, M.G. Rollins, and D.G. Long. 2001. Mapping fire regimes across time and space: Understanding coarse and fine-scale fire patterns. International Journal of Wildland Fire **10**:329-342.