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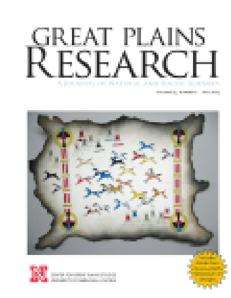

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ABSTRACT—Long-term knowledge of fire regimes aids in understanding the past, present, and future changes in Great Plains ecosystems. Dated fire scar histories and fire rate metrics in the Great Plains allow for quantitative analysis of the effects of climate on fire occurrence, frequency, forcing factors, and probability. Up to three centuries of fire scar data combined with modeling results from Great Plains sites show that spatially, fire frequency was greatly affected by annual maximum temperature from north to south, by annual precipitation east to west, by their interactions, and by precipitation thresholds. A fire-climate model, PC2FM (Physical Chemistry Fire Frequency Model), calibrated with rate metrics (mean fire intervals) derived from fire history data, estimates that in the Great Plains, fire intervals ranged from <4 to >30 years. A "precipitation threshold" divides the Great Plains into eastern and western fire regime regions along an approximate 60–100 cm north-south annual precipitation isohyet. Future changes in annual wildland fire probability at 1.2 km^2 are predicted to change from −10% to 70% in the Great Plains. Midlatitude regions of the Great Plains (Wyoming, eastern Colorado, Nebraska, Kansas, and South Dakota) are expected to increase the most in annual fire probability while some areas in Texas will decrease in fire probability due to fuel limitations.

Key Words: dendrochronology, fire scars, Great Plains, modeling, physical chemistry

Introduction

Historic wildland fire records and rate metrics can aid many of our land management decisions, natural resource policies, and understanding of ecosystem processes. Fire regime reference conditions based on historical archives are often a basis for fire management plans. National parks, such as Capulin Volcano and Devils Tower National Monuments, use information on past fire to manage vegetation (Guyette et al. 2006; Stambaugh et al. 2008). Knowledge of fire regime dynamics over long time-scales (e.g., centuries) gives a quantitative perspective on temporally changing factors influencing fire frequency (e.g., climate, ignitions, grazing, suppression). Fire histories from dated fire scars are commonly used to describe fire frequency, extent, severity, and seasonality but also provide fire rate metrics for models based in physics and chemistry. High between-site variability can exist in fire regimes at relatively small scales due to factors such as elevation, aspect, and ignition rates; nonetheless, climate, the focus of this paper, is an overarching influence on combustion rates and fuels. The objectives of this study were to (1) identity and collect fire scar data in new regions of the Great Plains, (2) summarize new and existing fire scar data in the Great Plains, (3) develop a regional fire regime model linking climate and fire data, and (4) discuss future fire probability and prediction in the Great Plains (Guyette et al. 2014).

To study climate and fire in the Great Plains, we use an approach that involves the principles of physical chemistry, fire ecology, and statistics. The theory and "law" of all these sciences were used to develop, calibrate, and validate hybrid regression equations giving each step in the model multiple points for testing. In particular we used the structure of the Physical Chemistry Fire Frequency Model (PC2FM) and the reformulation of the Arrhenius equation—a fundamental equation predicting

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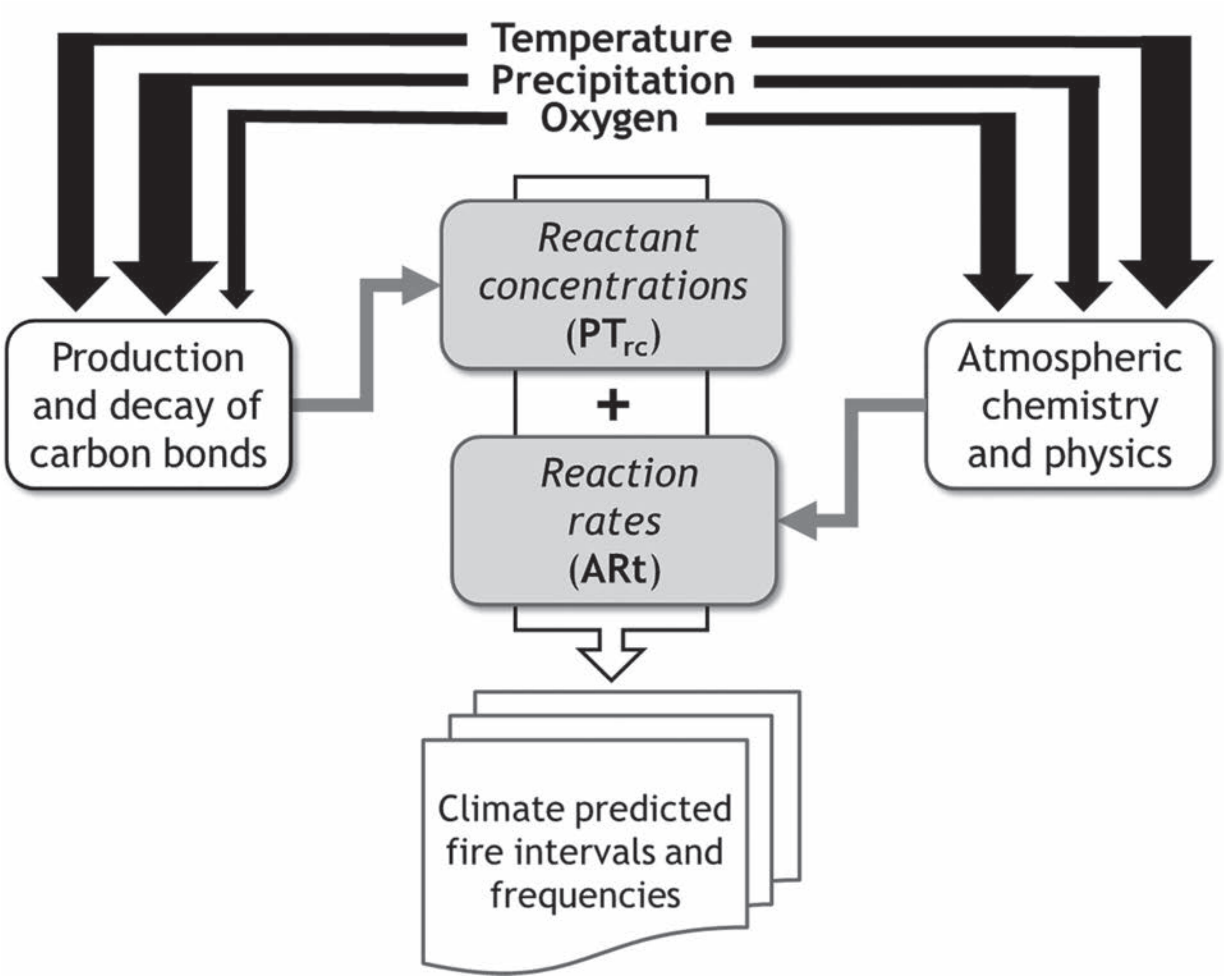

Figure 1. This conceptual diagram of the Physical Chemistry Fire Frequency Model (PC2FM) shows the interaction of its structural components (precipitation and temperature). Temperature and precipitation are used to develop proxies for combustion reaction rates (ARt) and available fuels (PT_{rc}). Temperature and precipitation interactions are embedded in both biological (carbon bonds) and combustion processes (physical chemistry) with ecosystems. The width of the arrows illustrates variable and component importance. For instance, precipitation is strongly involved in the growth of plants (carbon bond production) but less so in the inhibition of reactions rates in ecosystems.

rate constants (Equation 1)—to model fire in the Great Plains. A detailed explanation of the PC2FM and its physical chemistry and dendrochronology can be found in previous publications (Guyette et al. 2012, 2014). This approach combines the mechanistic components of the Arrhenius equation (Atkins 1986) and rate concentration equations (Harris 1987), as well as the deterministic components of statistical model calibration and validation. We selected and developed the two PC2FM components (Equation 1) based on literature and knowledge of both physical chemistry laws and ecosystem fire ecology. We tested and chose PC2FM parameters based on mechanistic and ecological relevance, statistical significance and explanatory power, and to a lesser extent, the availability of mapped climate data.

Methods

Fire Scar History Data Collection

We selected 19 potential fire history sites from national parks, forests, and grasslands, and from private lands within and adjacent to the Great Plains. We assessed the potential for fire scar history studies by searching for grasslands with trees or remnant wood with annual rings extending sufficiently back in time to exclude modern industrial, agricultural, and climate changes. New sites, due to their contribution to increased climate variance, are important additions for model calibration statistics in the Great Plains and make significant contributions toward quantifying and revealing the pre-climate-change fire frequency within the larger Great

Plains region. In addition to the new fire sites done for this study, we reviewed fire history sites in the Great Plains literature and included data from those sites in the regional fire scar calibration (Table 1). We found an additional 24 published studies, many with several fire scar sites. Fire scar data from new studies and existing publications ranged greatly in climate and included all the states of the Great Plains with the exception of Iowa.

We constructed fire histories from fire scars on three species: post oak (*Quercus stellata*, three sites), ponderosa pine (*Pinus ponderosa*, nine sites), and eastern redcedar (*Juniperus virginiana*, two sites). Fire histories ranged in length from 248 years (Lazy S-B Ranch, Chautauquah Hills, Kansas) to 691 years (Devils Tower National Monument, Wyoming) (Table 1). The mean length of fire scar records was 360 years.

Two possible opposite biases that can affect the fire scar record are (1) trees are not always scarred in a fire and (2) the spatial area required to produce a fire record may not always be 100% burned. Thus, a sample tree's fire record may have less frequent fire scars than the number of fires (condition 1), or not all the sample area was burned, causing more frequent estimates of fire than would be found at a point location (condition 2). We do know from field studies that trees without any scars often grow next to trees with many scars and thus know that more samples in the smallest area make the best record. We used the composite fire scar record "as is," without filtering by the percentage or number of trees that were scarred (Dieterich 1980). We minimized this multiple bias problem by definition: a fire scar represents a fire in all or part of a 1 km^2 area.

At each site, we collected 20 to 50 sample trees usually within a 1 km^2 area. From many years of experience, especially in the more humid eastern North American regions, we believe this is the smallest area with enough solid stumps, snags, and trees to provide data on low- to high-intensity surface fires (Guyette and Stambaugh 2004). We cut cross sections from snags, stumps, and trees near 30 cm above ground level and where the fire scar record was best preserved. We geographically referenced site and sample locations using a GPS. We air-dried cross sections and then polished their surfaces cut using ANSI 600 grit sandpaper to reveal cellular detail of the annual rings. We measured annual rings on samples to an accuracy of 0.01 mm using a moving stage with an electronic transducer and binocular microscope. We plotted tree-ring measurements and visually crossdated (Stokes and Smiley 1968; Baillie 1982). We also imported digital measurement files to COFECHA (Holmes et al. 1986, 41–49), a program that checks the accuracy of dating and aids in quality control of measurements. We supplemented visual matching of ring-width series plots by using statistical analysis of dating precision. We dated sample ring-width patterns utilized new tree-ring series (dated ring-widths from cores taken at or near the fire history sites (Purtis Creek, Devils Tower, Sand Creek, Wichita Mountain, Loess Hills) (Table 1) or from existing chronologies developed at the Missouri Tree-Ring Laboratory, or existing chronologies available from the International Tree-Ring Data Bank (http://www.ngdc.noaa.gov/paleo/ftp-treering.html). Once annual rings were absolutely dated, we assigned fire scars to the calendar year of the first growth response to the fire injury (e.g., callus tissue, cambial death). If possible, we dated fire scars to the season of occurrence based on scar position within the annual ring (Swetnam and Baisen 1996). Using FHX2 software (Grissino-Mayer 1996), we developed the fire scar chronology and analyzed fire scar event years. We computed mean fire return intervals (MFIs) for sites with composite fire intervals (Guyette et al. 2010a, 2010b). Although fire interval data are often skewed and better described by Weibull distributions, they are much less available for the 168 sites (now 191 sites, as this is a "living model"). When the Weibull distribution is used it is often only slightly different than mean fire intervals, and when compared to the other non–climate noise in fire regimes, it is small. Also, many sites with only a few longer intervals are not appropriate for this distribution as are long fire intervals from a few high-resolution charcoal sites (Lynch et al. 2004).

Fire Interval Modeling

The physical chemistry of ecosystem combustion can be understood and modeled with broad-based variance in important combustion variables such as the energy and concentration of reactant molecules (O_2 and $C_6H_{12}O_6$) and reactant inhibitors (H_2O) from molecular to ecosystem scales. The mathematical formulation of the concepts and processes of the PC2FM is given below (Equation 1). The process of wildland fire begins at the molecular level with an exothermic reaction. This process of formulation, calibration, and validation of the PC2FM begins by breaking down wildland fire into a reaction parameter (ARt), primarily temperature and humidity, and a reactant concentration parameter (PT_{rc}), primarily carbon bonds and oxygen (Figure 1). The names of the reaction environment component (ARt)

TABLE 1. Fire and time data from this study and the literature in and near the Great Plains.

Site name	State	Location	Site no.	Record length of fire interval	Dominant vegetation	Early[1] MFI < ~1 km²	Late[2] MFI < ~1 km²	Model[3] MFI	Reference
Wichita Mountains	OK	34°450'N, 98°380'W	4	1724–2004	Grass, oak	8.8, 6.3, 6.5, 12.3	2.6, 3.2, 3.6, 2.7	2.0–6.0	Stambaugh et al. 2014
Cherokee Nation	OK	36°15'N, 94°45'W	1	1633–1992	Pine, oak, grass	5.0–2.5	1.7–2.2	4.0–6.0	Stambaugh et al. 2013
West Ash Creek	NE	42°39'N, 103°15'W	2	1571–1936	Grass, pine	14, 22	6.8, 10	8–10	This study
Prairie Edge	OK	36°10'N, 96°18'W	1	1772–1889	Grass, oak	4.9	3.4	2–4	Clark et al. 2007
Cross Timbers	OK	35°38'N, 96°02'W	1	1750–1899	Grass, oak	5.9	3	2–4	DeSantis et al. 2010
Aiken Canyon Park	CO	38°38'N, 104°53'W	1	1695–1952	Grass, woodland	19	9.7	20–22	Wieder and Bower 2004
Loess Hills	MO	40°27'N, 95°34'W	1	1671–1980	Bur oak, grass	6.6	2.5	6–8	Stambaugh et al. 2006
Cedar Glades National Forest	MO	36°42'N, 92°46'W	1	1730–1980	Juniper, grass	3.2	22	6–8	Guyette and McGinnes 1982
Mississippi Hills	IO	42°32'N, 90°50'W	1	1714–1850	Oak, grass	5	n/a	7–9	This study
Oak woodland	IL	38°08'N, 88°40'W	1	1775–1995	Oak, grass	3.9	3.0	6–8	McClain et al. 2010
Devils Tower National Park	WY	44°35'N, 104°42'W	1	1315–1886	Grass, pine	21	23	18–24	Stambaugh et al. 2008
Lake Itasca State Park	MI	47°13'N, 95°12'W	3	1756–1910	Pine	27, 27, 27	9.4, n/a, n/a	16–20	Brown et al. 2004
Lake Itasca State Park	MI	47°13'N, 95°12'W	1	1714–1953	Pine	25	n/a	16–20	Spurr 1954
Purtis Creek State Park	TX	32°21'N, 95°59'W	1	1690 2008	Post oak	6.7	14.6	2–4	Stambaugh et al. 2011
Capulin Volcano	NM	36°47'N, 103°57'W	2	1601–1966	Pine, grass	11.3, 7.6	29, n/a	6–10	Guyette et al. 2006
Col. and Wyo. 5° gradient MKC	CO	40°24'N, 105°12'W	1	1701–1990	Pine	27	n/a	22–26	Brown and Shepperd 2001
Col. and Wyo. 5° gradient ASU	WY	42°20'N, 105°25'W	1	1460–1909	Pine	37	n/a	30–35	Brown and Shepperd 2001
Col. and Wyo. 5° gradient BLM	CO	37°51'N, 105°16'W	1	1608–1805	Pine	25	n/a	22–24	Brown and Shepperd 2001
Black Hills: Jewel Cave National Monument	SD	43°40'N, 103°45'W	4	~1650-1890	Pine	23, 20, 21, 32	9, 26, 9, 11	14–24	Brown and Sieg 1996
Black Hills: Wind Cave National Park	SD	43°35'N, 103°25'W	3	1652–1910	Pine, grass	15, 14, 20	9.5, 9.5, 20		Brown and Sieg 1999
Lazy S-B Ranch	KS	37°29'N, 95°40'W	1	1765–2004	Oak, grass	NA	2.7	4–6	This study
White Ranch State Forest	MO	36°32'N, 91°50'W	1	1711–1960	Oak, grass	3.7	7.6	4–6	Dey et al. 2004

Site name	State	Location	Site no.	Record length of fire interval	Dominant vegetation	Early[1] MFI < ~1 km²	Late[2] MFI < ~1 km²	Model[3] MFI	Reference
Caney Mountain	MO	36°40'N, 92°25'W	2	1656–1985	Oak, grass	6.0	7.5	4–6	Guyette and Cutter 1991
Niobrara 1	NE	42°45'N, 99°57'W	1	1736 1971	Grass, pine	11	6	6–8	Bragg 1985
Niobrara 2	NE	42°47'N, 99°57'W	1	1572 1997	Grass, pine	10	13	6–8	This study
Wildcat Hills	NE	41°45'N, 103°49'W	1	1515–1733	Grass, pine	27	n/a	8–10	This study
Theodore Roosevelt National Park	ND	46°58'N, 103°26'W	1	1576–1960	Grass, juniper	24	13	10–12	This study
Theodore Roosevelt National Park	ND	46°57'N, 103°20'W	1	1598–1936	Grass, pine	12.3	13.4	10–12	Brown 1996
Theodore Roosevelt National Park	ND	46°57'N, 103°20'W	1	1816–1936	Grass, juniper	17	n/a	10–12	Brown 1996
Lost Creek	MT	47°32'N, 107°19'W	1	1702–1901	Grass, pine	32	12	18–22	This study
Soda Creek	MT	47°30'N, 107°56'W	1	1762 1908	Grass, pine	15.5	n/a	18–22	This study
Guadalupe Mountains (low)	TX	31°54'N, 104°49'W	1	1700–1922	Pine, grass	15.9	n/a	8–10	Sakulich 2004
Guadalupe Mountains (medium)	TX	31°54'N, 104°49'W	1	1700–1922	Pine and grass	12.7	n/a	10–12	Sakulich 2004
Guadalupe Mountains (high)	TX	31°54'N, 104°49'W	1	1700–1922	Pine, grass	17.8	n/a	10–12	Sakulich 2004
Davis Mountains	TX	30°36'N, 104°07'W	1	1772–1937	Pine, grass	4.4	8.9	2–4	Camp et al. 2006
Big Bend National Park	TX	29°15'N, 103°18'W	1	1786–1937	Pine, grass	8.3	13.8	8–12	Camp et al. 2006

Note: The primary modeling and new data results here are in the three MFI (mean fire interval in years) columns. "Early MFI" represents fire mean fire scar data before 1850 (1890*), "Late MFI" represents fire scar data after 1850. Only "Early" data is used in modeling. n/a = not available.

and the reactant concentration term (PTrc) are given below the model components.

$$MFI = A_o \boldsymbol{e}^{(E_a/RT)} + 1/(P^2/T) \qquad \text{(Equation 1)}$$
$$\text{(ARt)} \qquad (PT_{rc}) \qquad \text{(Rate \& Intensity)}$$

Here, MFI is the mean fire interval, the *Ao* term = P2/*pp* O_2, $\boldsymbol{e}$ = 2.718, *Ea* = 132 kJ mol^{-1} and is a constant in this model formulation, *R* = 0.00831 kJ mol^{-1} K^{-1} (the universal gas constant), *P* = annual precipitation in cm, *T* = degrees K.

These terms and the model were then developed and tested empirically with mean fire interval data from 168 sites, more than 3,400 trees, with 30,000 fire scars (Guyette et al. 2012, Supplemental Data). We used multiple regression analysis to test the PC2FM. Regression coefficients translated the relatively fine-scale units of chemistry (i.e., kJ^{-1} mol^{-1}, molecular reactions per second, and partial pressure of oxygen) to the landscape-scale (~1 km^2) mean fire intervals (MFI), relative frequency and probability (1/MFI) (Keller and Warrack 1997, 30). We converted temperature data from Fahrenheit or Celsius to Kelvin units to more closely follow the thermodynamic principles behind the Arrhenius equation.

Climate Data

Currently the PC2FM utilizes three covariates of MFIs: annual mean maximum temperature (*Tmax*), annual mean precipitation (*P*), and the estimated partial pressure of oxygen. Climate data from published fire histories, when available and from PRISM data (Daly 2004), were used for site climate. The partial pressure of oxygen (Figure 1) is estimated from elevation (Jacobson 2005). Climate covariates represent averages for the 1971–2000 CE (30 yr) period. The *Tmax* data used for calibration are a "proxy" in the sense that the model period (~1650–1850 CE) is different than the climate data period (1971–2000 CE). We maintain that errors caused by this difference in time period are minimal compared to the spatial variability in temperature.

Global temporal temperature differences of approximately 0.4°C from 1750 to 1970 CE are small (Mann et al. 1998) compared to the large differences in the spatial variability of temperature. A range of more than 26°C in temperature exists among fire-climate data sites. Difference in temperature among fire-climate calibration sites range from lows of −3.7°C (Fastie et al. 2003), −8.3°C (Lynch et al. 2004), and −12.0°C (Dury and Grissom 2008) to highs of 26.1°C (Huffman 2006), 26.6°C (Kaib et al. 2000), and 25.8°C (Stambaugh et al. 2011).

Mapping

We mapped PC2FM estimates of MFI_{cf} (MFI climate forced) using ESRI 2011. We applied grid data mean maximum temperature and mean annual precipitation data (PRISM data; Daly et al. 2004) to Equation 1 to produce grid estimates of MFIs for the pre-Euro-American settlement period (~1650 to 1850 CE). We mapped using the 800 m grid product. The values represent the model resolution. We did not interpolate between grid points.

Results

Overall Great Plains Fire Statistics

We sampled a total of 418 trees at 14 sites. We recorded a total of 370 fires from 996 fire scars. We sampled 62 trees (about 15% of the total) thast had no scars. We sampled those trees because there exterior surface indicated possible internal scarring. Of the trees with scars, the average number of scars per tree was about 2.8. The highest percentage of trees scarred occurred at a ponderosa pine parkland (Lost Creek, Charles M. Russell National Wildlife Refuge, MT). For all sites, mean fire intervals (MFIs) during the pre-Euro-American period (approximately pre-1850) averaged 13.2 years and ranged from 4.8 to over 28 years. Longer fire intervals (>28 years) likely occurred in the Great Plains, particularly at sites in the cooler northern regions and sites with topographic features that inhibited fire spread, fuel production (e.g., badlands), and macroclimatic influences. Slightly shorter intervals likely occurred in flatter, larger contiguous grasslands where single ignitions could result in large fire events in a relatively short period.

At the Great Plains regional scale, we found average mean maximum temperature ($r = -0.81$) and annual precipitation ($r = -0.49$) were significantly, negatively, and linearly correlated with mean fire intervals as determined from composite fire scar intervals at 44 fire history sites. However, the most important difference between fire frequency and these climate variables is expressed statistically by their coefficients of determinations, where temperature has a linear relationship to fire frequency compared with the nonlinear relationship between precipitation and fire frequency.

We found modeling results with both continental and Great Plains fire scar data sets were significant ($r^2 > 0.76$, $p < 0.001$). Both PC2FM models had identical formulations with the exception of the coefficients, which vary with the two data sets used. However, the conti-

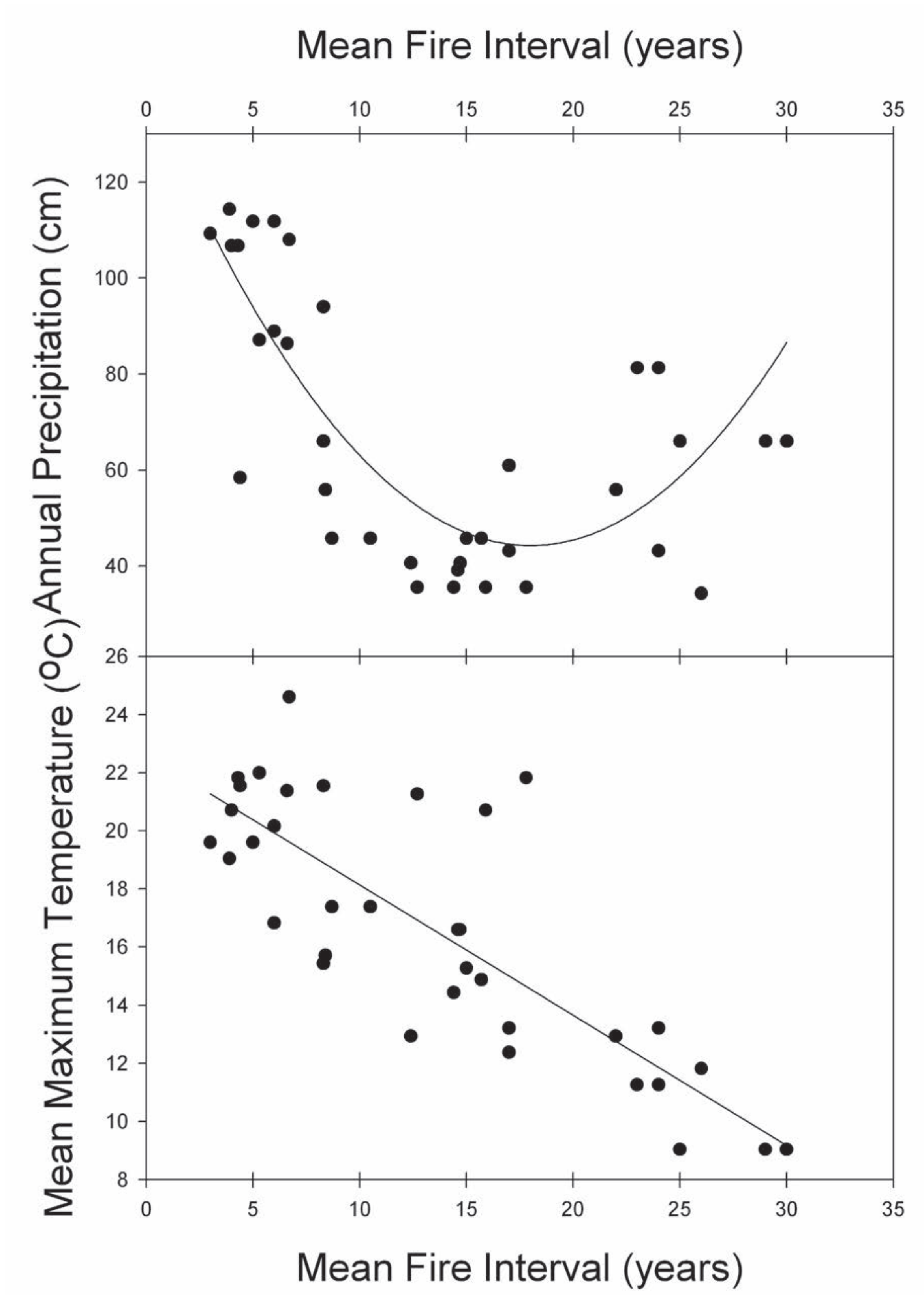

Figure 2. Scatter plots of mean fire intervals plotted by precipitation (top) and temperature (bottom) (PRISM climate data; Daly et al. 2004). Fire data include Great Plains region and adjacent grasslands. While the relationship between temperature and mean fire intervals alone is linear (r^2 = −0.68), the relationship between annual precipitation and mean fire intervals is more complex. The second-order polynomial regression (r^2 = 0.58) line illustrates the relationship where changes in precipitation can either increase or decrease fire frequency at different site temperature.

$$MFI_{gp} = -1.68 + (3.48^{-28} \times ARt) + (81.0 \times PT_{rc}) \quad \text{(Great Plains, Eq. 2)}$$

$$MFI_{c} = 0.545 + (4.16^{-27} \times ARt) + (49.8 \times PT_{rc}) \quad \text{(Continental, Eq. 3)}$$

Where:

MFI_{cf}	is *climate forced* mean fire interval (years),
$ARt = A_o exp^{(Ea/(RT))}$;	is the Arrhenius term,
$A_o = (P^{2.017})(_{pp}O_2)$;	is estimated reactants concentration,
$Ea = 133\ kJ\ mol^{-1}(P^{(P/T)0.0000375})$;	is estimated activation energy term,
$R = 0.0083\ kJ^{-1}\ mol^{-1}$;	is the Universal Gas constant,
T = mean max temperature in ^{o}K (adjusted -0.4°C for warming);	is degrees Kelvin (1970-2000),
Exp;	is 2.718,
P = annual precipitation (cm);	is 30 year mean precipitation (1970-2000),
$_{pp}O_2$ = partial pressure of oxygen;	is based on: (0.2095) $exp^{(-0.12*elevation(in\ km))}$,
$PT_{rc} = 1/(P^2/T)$;	is the moisture index.

Figure 3. Details of two PC2FM from the Great Plains data only (Equation 2, n = 44, r^2 = 0.76) and from continental fire history data set (Equation 3, n =168, r^2 = 0.78). PC2FM components for the two models, their details, and explanations of their units are given below the equations.

nental data calibration (Figure 3, Equation 2) is much broader in climatic scale and better estimates spatial and temporal climate-fire extrapolation in the Great Plains. As ecosystems get smaller they have much less variance in climate making fire frequency modeling more effected by non-climatic variables. A review of Great Plains fire scar histories at 44 sites from many publications and this study (Table 1) reveals that the early record of mean fire intervals (Table 1, Column 7, Early MFI, ~1 km²/yr) is consistent with modeled estimates of MFI at the sites (Table 1, Column 9). We used pre-1850 fire-climate data to avoid the effects of climate change. Perhaps the most important aspect of this modeling result is that a rate metric of the fire scar record is validated by the physics of the combustion of solid materials.

Site MFIs alone provide only snapshots of mean fire intervals in the Great Plains because of limited spatial and temporal coverage. To provide a general spatial average of climate-modeled MFIs (Figure 3, Equation 3) for the Great Plains, we averaged all 1 km² MFI estimates within the study region. The resulting spatial average of MFIs for the entire Great Plains was 9.5 years. The model estimated that 86% of the Great Plains area had MFIs that averaged between 3 and 13 years. Less than 1% of the Great Plains area had MFIs shorter than 3 years while 13% of the Great Plains had MFIs longer than 13 years. Modeled estimates of mean fire intervals based only on temperature, precipitation, and the partial pressure of oxygen compared well with actual fire scar data. The PC2FM explained 76% to 78% of the variance in the mean fire intervals of the two calibration data sets (Figure 3).

We used available basic combustion variables in the PC2FM to map coarse-scale climate-driven fire frequency. As expected, the south-to-north decrease in molecular energy (temperature) has a profound effect on combustion in this somewhat homogeneous (grassland) region. Less expected was the longitudinal effect on fire frequency of the interaction between temperature and precipitation.

Model results (Figure 4) predict where and to what degree changes in precipitation affect fire frequency. In Figure 4, the blue line follows the 62 to 100 cm annual "precipitation threshold" (depending on temperature) for the positive versus the negative effects of precipitation on fire frequency. Increased precipitation will increase potential fire frequency west of the blue threshold line and slightly decrease potential fire east of the line. Decreased precipitation will decrease potential fire frequency west of the blue threshold line and slightly increase potential fire frequency east of the line.

Discussion

Precipitation Effects in the Great Plains

We found the model offers some counterintuitive results at first, but the results make sense when con-

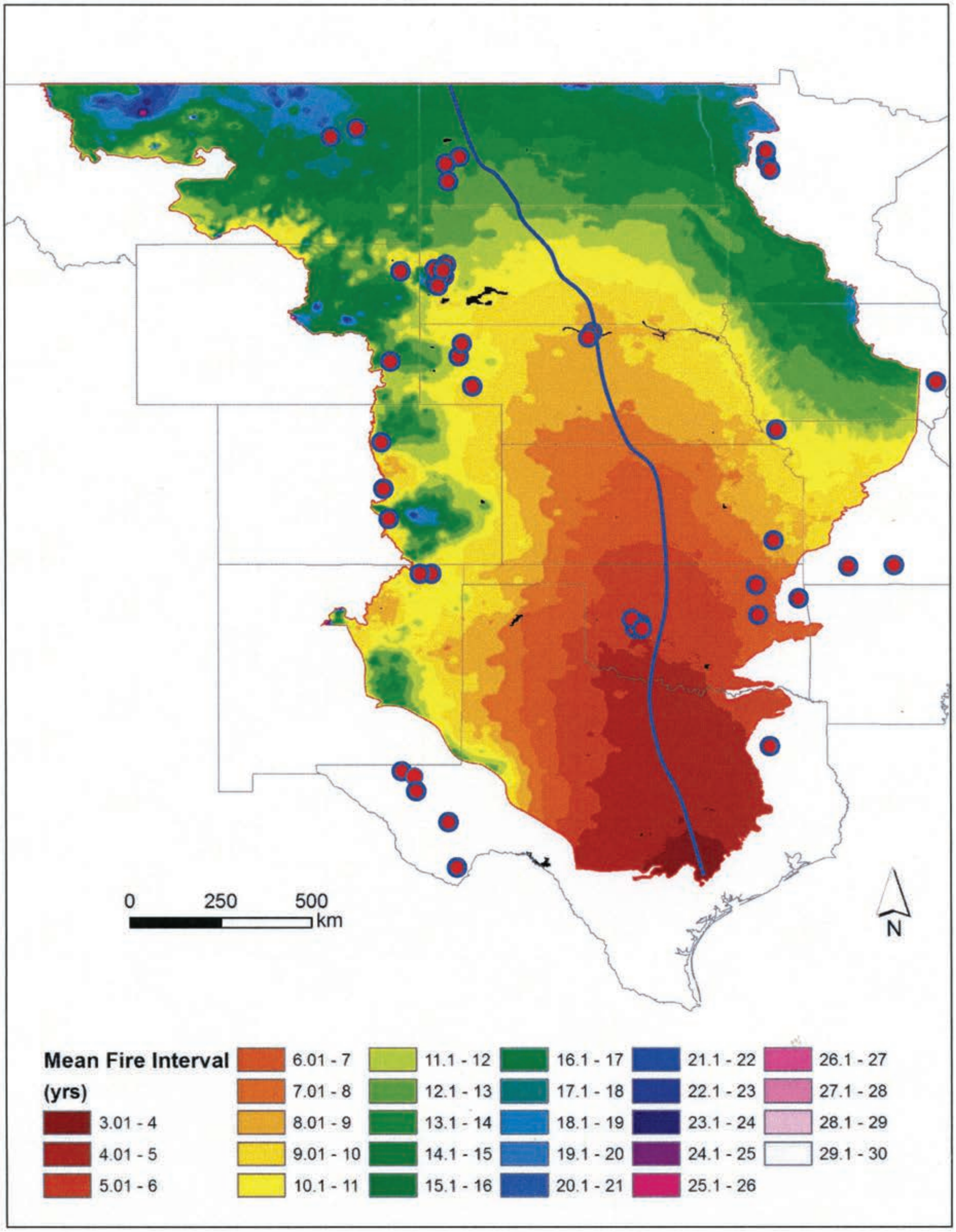

Figure 4. Mapped estimates of mean fire intervals (MFIS) in the Great Plains during the pre-Euro-American period (~1650–1850) as calculated from climate variables in the PC2FM (Figure 3, Eq. 2). "Climate thresholds" or "combustion process tipping points" are shown with the blue line. Climate-based thresholds within the PC2FM equation indicate that to the west of the blue line in the Great Plains there exists a positive response (increased fuel, PT_{rc}) of fire frequency to increased precipitation in fuel-limited ecosystems. Conversely, a negative response (increased fuel moisture and humidity, AR_t) of fire frequency to increased precipitation exists in the Great Plains to the east of the blue line. Red-filled circles are fire scar data studies done by many workers over many years within and near the Great Plains (see Table 1 for their references). National parks are shown in black.

sidering combustion dynamics and fire ecology. Less precipitation means fewer carbon bonds produced and less to burn. However, this works only in fuel-limited ecosystems. Modeling and fire ecology both show that precipitation has two important but counteracting influences on fire regimes, especially in the Great Plains. The primary influence of precipitation is on fuel production and decay while a secondary influence of precipitation pertains to humidity, decreased reactant collision frequency, and the increased activation energy (E_a) needed with higher fuel moistures. Using the principles of physical chemistry, both of these influences are integrated into the PC2FM. The PC2FM output quantifies an ecological principle, "the law of limits" concerning temperature and precipitation in the ecosystem's climate responses to fire occurrence. Some ecosystems, particularly those in the Great Plains, have climate conditions near "precipitation thresholds" that have the potential to "cross over" and change the primary combustion process from fire rate conditions to fuel concentration. For instance, the "ridge" pattern of PC2FM emanating from the southern Great Plains northward (Figure 4) is the result of the positive and negative effects of precipitation on fire frequency.

Temperature Effects in the Great Plains

Model results indicate that temperature differences result in varied response of MFIS to precipitation. This may force changes in MFIS due to temperature-precipitation interactions through global warming alone. Climate forcing of fire frequency can be bidirectional resulting from precipitation *and temperature* changes along the 60–100 cm annual precipitation totals in the Great Plains. In a scenario where mean maximum temperatures homogeneously increase, the model suggests decreases in fire frequency west of the 60–100 cm annual precipitation line by reducing fuel production. Conversely, modeling results indicate that increases in temperature east of the 60–100 cm annual precipitation line in the Great Plains are expected to cause slightly increased fire frequency using both models (Figure 3, Equations 2 and 3).

Climate-Forced Future Changes in Great Plains Fire

The large area of the Great Plains offers enough climate variance in combustion variables for developing equations that overcome the many nonclimatic factors in fire regimes. Recent work predicting changes in climate-forced fire probabilities used the PC2FM calibrated with 170 sites, 30 (18%) of which were in the Great Plains biome (Guyette et al. 2014). Low resolution (~ 3.75° to 2.5° longitude from equator) climate data based primarily on global climate change (GCMS) estimates of precipitation and temperature were put into the PC2FM for mapping of fire probability changes between 2000 and 2090. This modeling effort indicated fire probabilities in the mid- and northern Great Plains would increase. Estimates of large scale (~ 40,000 km^2) fire probabilities differ in the Great Plains from north to south. Modeling of PC2FM using global climate change model predictions indicate that the mid- and northern latitudes of the Great Plains would increase in climate-forced fire probability while the southern region of the Great Pains would decrease in climate-forced fire probability. The least amount of climate-forced fire probability change would occur in northern Texas and in parts of Oklahoma and New Mexico.

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