An Analytic Approach to Climate Dynamics and Fire Frequency in the Great Plains

Richard P. Guyette, Michael C. Stambaugh, Joseph Marschall, Erin Abadir

Great Plains Research, Volume 25, Number 2, Fall 2015, pp. 139-150 (Article)

Published by University of Nebraska Press

DOI: 10.1353/gpr.2015.0031
An Analytic Approach to Climate Dynamics and Fire Frequency in the Great Plains

Richard P. Guyette, Michael C. Stambaugh, Joseph Marschall, and Erin Abadir

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 km² 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...
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.
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, Chautauqua 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 km² area.

At each site, we collected 20 to 50 sample trees usually within a 1 km² 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 (O₂ and C₆H₁₂O₆) and reactant inhibitors (H₂O) 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 (PTc), primarily carbon bonds and oxygen (Figure 1). The names of the reaction environment component (ART)
<table>
<thead>
<tr>
<th>Site name</th>
<th>State</th>
<th>Location</th>
<th>Site no.</th>
<th>Record length of fire interval</th>
<th>Dominant vegetation</th>
<th>Early(^t) MFI</th>
<th>Late(^t) MFI</th>
<th>Model(^t) MFI</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wichita Mountains</td>
<td>OK</td>
<td>34°450'N, 98°380'W</td>
<td>4</td>
<td>1724–2004</td>
<td>Grass, oak</td>
<td>8.8, 6.3, 6.5, 12.3</td>
<td>2.6, 3.2, 3.6, 2.7</td>
<td>2.0–6.0</td>
<td>Stambaugh et al. 2014</td>
</tr>
<tr>
<td>Cherokee Nation</td>
<td>OK</td>
<td>36°15'N, 94°45'W</td>
<td>1</td>
<td>1633–1992</td>
<td>Pine, oak, grass</td>
<td>5.0–2.5</td>
<td>1.7–2.2</td>
<td>4.0–6.0</td>
<td>Stambaugh et al. 2013</td>
</tr>
<tr>
<td>West Ash Creek</td>
<td>NE</td>
<td>42°39'N, 103°15'W</td>
<td>2</td>
<td>1571–1936</td>
<td>Grass, pine</td>
<td>14, 22</td>
<td>6.8, 10</td>
<td>8–10</td>
<td>This study</td>
</tr>
<tr>
<td>Prairie Edge</td>
<td>OK</td>
<td>36°10'N, 103°15'W</td>
<td>1</td>
<td>1772–1889</td>
<td>Grass, oak</td>
<td>4.9</td>
<td>3.4</td>
<td>2–4</td>
<td>Clark et al. 2007</td>
</tr>
<tr>
<td>Cross Timbers</td>
<td>OK</td>
<td>35°38'N, 96°02'W</td>
<td>1</td>
<td>1750–1899</td>
<td>Grass, oak</td>
<td>5.9</td>
<td>3</td>
<td>2–4</td>
<td>DeSantis et al. 2010</td>
</tr>
<tr>
<td>Aiken Canyon Park</td>
<td>CO</td>
<td>38°38'N, 104°53'W</td>
<td>1</td>
<td>1695–1952</td>
<td>Grass, woodland</td>
<td>19</td>
<td>9.7</td>
<td>20–22</td>
<td>Wieder and Bower 2004</td>
</tr>
<tr>
<td>Loess Hills</td>
<td>MO</td>
<td>40°27'N, 95°34'W</td>
<td>1</td>
<td>1671–1980</td>
<td>Bur oak, grass</td>
<td>6.6</td>
<td>2.5</td>
<td>6–8</td>
<td>Stambaugh et al. 2006</td>
</tr>
<tr>
<td>Cedar Glades National Forest</td>
<td>MO</td>
<td>36°42'N, 92°46'W</td>
<td>1</td>
<td>1730–1980</td>
<td>Juniper, grass</td>
<td>3.2</td>
<td>22</td>
<td>6–8</td>
<td>Guyette and McGinnes 1982</td>
</tr>
<tr>
<td>Mississippi Hills</td>
<td>MO</td>
<td>42°32'N, 90°50'W</td>
<td>1</td>
<td>1714–1850</td>
<td>Oak, grass</td>
<td>5</td>
<td>n/a</td>
<td>7–9</td>
<td>This study</td>
</tr>
<tr>
<td>Oak woodland</td>
<td>IL</td>
<td>38°08'N, 88°40'W</td>
<td>1</td>
<td>1775–1995</td>
<td>Oak, grass</td>
<td>3.9</td>
<td>3.0</td>
<td>6–8</td>
<td>McClain et al. 2010</td>
</tr>
<tr>
<td>Devils Tower National Park</td>
<td>WY</td>
<td>44°35'N, 104°42'W</td>
<td>1</td>
<td>1315–1886</td>
<td>Grass, pine</td>
<td>21</td>
<td>23</td>
<td>18–24</td>
<td>Stambaugh et al. 2008</td>
</tr>
<tr>
<td>Lake Itasca State Park</td>
<td>MI</td>
<td>47°13'N, 95°12'W</td>
<td>1</td>
<td>1714–1953</td>
<td>Pine</td>
<td>25</td>
<td>n/a</td>
<td>16–20</td>
<td>Spurr 1954</td>
</tr>
<tr>
<td>Purtis Creek State Park</td>
<td>TX</td>
<td>32°21'N, 95°59'W</td>
<td>1</td>
<td>1690 2008</td>
<td>Post oak</td>
<td>6.7</td>
<td>14.6</td>
<td>2–4</td>
<td>Stambaugh et al. 2011</td>
</tr>
<tr>
<td>Capulin Volcano</td>
<td>NM</td>
<td>36°47'N, 103°57'W</td>
<td>2</td>
<td>1601–1966</td>
<td>Pine, grass</td>
<td>11.3, 7.6</td>
<td>29, n/a</td>
<td>6–10</td>
<td>Guyette et al. 2006</td>
</tr>
<tr>
<td>Col. and Wyo. 5° gradient MKC</td>
<td>CO</td>
<td>40°24'N, 105°12'W</td>
<td>1</td>
<td>1701–1990</td>
<td>Pine</td>
<td>27</td>
<td>n/a</td>
<td>22–26</td>
<td>Brown and Shepperd 2001</td>
</tr>
<tr>
<td>Col. and Wyo. 5° gradient ASU</td>
<td>WY</td>
<td>42°20'N, 105°25'W</td>
<td>1</td>
<td>1460–1909</td>
<td>Pine</td>
<td>37</td>
<td>n/a</td>
<td>30–35</td>
<td>Brown and Shepperd 2001</td>
</tr>
<tr>
<td>Col. and Wyo. 5° gradient BLM</td>
<td>CO</td>
<td>37°51'N, 105°16'W</td>
<td>1</td>
<td>1608–1805</td>
<td>Pine</td>
<td>25</td>
<td>n/a</td>
<td>22–24</td>
<td>Brown and Shepperd 2001</td>
</tr>
<tr>
<td>Black Hills: Jewel Cave National Monument</td>
<td>SD</td>
<td>43°40'N, 103°45'W</td>
<td>4</td>
<td>~1650–1890</td>
<td>Pine</td>
<td>23, 20, 21, 32</td>
<td>9, 26, 9, 11, 14–24</td>
<td>1996</td>
<td>Brown and Sieg 1996</td>
</tr>
<tr>
<td>Lazy s-b Ranch</td>
<td>KS</td>
<td>37°29'N, 95°40'W</td>
<td>1</td>
<td>1765–2004</td>
<td>Oak, grass</td>
<td>NA</td>
<td>2.7</td>
<td>4–6</td>
<td>This study</td>
</tr>
<tr>
<td>White Ranch State Forest</td>
<td>MO</td>
<td>36°32'N, 91°50'W</td>
<td>1</td>
<td>1711–1960</td>
<td>Oak, grass</td>
<td>3.7</td>
<td>7.6</td>
<td>4–6</td>
<td>Dey et al. 2004</td>
</tr>
<tr>
<td>Site name</td>
<td>State</td>
<td>Location</td>
<td>Site no.</td>
<td>Record length of fire interval</td>
<td>Dominant vegetation</td>
<td>Early MFI &lt; ~1 km²</td>
<td>Late MFI &lt; ~1 km²</td>
<td>Model MFI</td>
<td>Reference</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-------</td>
<td>---------------------------</td>
<td>----------</td>
<td>-------------------------------</td>
<td>---------------------</td>
<td>-------------------</td>
<td>-------------------</td>
<td>-----------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Niobrara 1</td>
<td>NE</td>
<td>42°45’N, 99°57’W</td>
<td>1</td>
<td>1736 1971</td>
<td>Grass, pine</td>
<td>11</td>
<td>6</td>
<td>6–8</td>
<td>Bragg 1985</td>
</tr>
<tr>
<td>Niobrara 2</td>
<td>NE</td>
<td>42°47’N, 99°57’W</td>
<td>1</td>
<td>1572 1997</td>
<td>Grass, pine</td>
<td>10</td>
<td>13</td>
<td>6–8</td>
<td>This study</td>
</tr>
<tr>
<td>Wildcat Hills</td>
<td>NE</td>
<td>41°45’N, 103°49’W</td>
<td>1</td>
<td>1515–1733</td>
<td>Grass, pine</td>
<td>27</td>
<td>n/a</td>
<td>8–10</td>
<td>This study</td>
</tr>
<tr>
<td>Theodore Roosevelt National Park</td>
<td>ND</td>
<td>46°58’N, 103°26’W</td>
<td>1</td>
<td>1576–1960</td>
<td>Grass, juniper</td>
<td>2.4</td>
<td>13</td>
<td>10–12</td>
<td>This study</td>
</tr>
<tr>
<td>Theodore Roosevelt National Park</td>
<td>ND</td>
<td>46°57’N, 103°20’W</td>
<td>1</td>
<td>1816–1936</td>
<td>Grass, juniper</td>
<td>17</td>
<td>n/a</td>
<td>10–12</td>
<td>Brown 1996</td>
</tr>
<tr>
<td>Lost Creek</td>
<td>MT</td>
<td>47°32’N, 107°19’W</td>
<td>1</td>
<td>1702–1901</td>
<td>Grass, pine</td>
<td>32</td>
<td>12</td>
<td>18–22</td>
<td>This study</td>
</tr>
<tr>
<td>Soda Creek</td>
<td>MT</td>
<td>47°30’N, 107°56’W</td>
<td>1</td>
<td>1762 1908</td>
<td>Grass, pine</td>
<td>15.5</td>
<td>n/a</td>
<td>18–22</td>
<td>This study</td>
</tr>
<tr>
<td>Guadalupe Mountains (low)</td>
<td>TX</td>
<td>31°34’N, 104°49’W</td>
<td>1</td>
<td>1700–1922</td>
<td>Pine, grass</td>
<td>15.9</td>
<td>n/a</td>
<td>8–10</td>
<td>Sakulich 2004</td>
</tr>
<tr>
<td>Guadalupe Mountains (medium)</td>
<td>TX</td>
<td>31°54’N, 104°49’W</td>
<td>1</td>
<td>1700–1922</td>
<td>Pine and grass</td>
<td>12.7</td>
<td>n/a</td>
<td>10–12</td>
<td>Sakulich 2004</td>
</tr>
<tr>
<td>Guadalupe Mountains (high)</td>
<td>TX</td>
<td>31°34’N, 104°49’W</td>
<td>1</td>
<td>1700–1922</td>
<td>Pine, grass</td>
<td>17.8</td>
<td>n/a</td>
<td>10–12</td>
<td>Sakulich 2004</td>
</tr>
<tr>
<td>Davis Mountains</td>
<td>TX</td>
<td>30°36’N, 104°07’W</td>
<td>1</td>
<td>1772–1937</td>
<td>Pine, grass</td>
<td>4.4</td>
<td>8.9</td>
<td>2–4</td>
<td>Camp et al. 2006</td>
</tr>
<tr>
<td>Big Bend National Park</td>
<td>TX</td>
<td>29°15’N, 103°48’W</td>
<td>1</td>
<td>1786–1937</td>
<td>Pine, grass</td>
<td>8.3</td>
<td>13.8</td>
<td>8–12</td>
<td>Camp et al. 2006</td>
</tr>
</tbody>
</table>

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.

\[ MFI = A \cdot e^{Ea/R} + 1/(P\cdot T) \]  
\[ (Art) \quad (Pt, n) \]  
\[ \text{Rate & Intensity} \]

Here, MFI is the mean fire interval, the Ao term = P2/PPo2, e = 2.718, Ea = 132 kJ mol\(^{-1}\) and is a constant in this model formulation, \( R = 0.00831 \text{ kJ mol}^{-1} \text{K}^{-1} \) (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 multiple regression analysis to test the pc2fm. Regression (Guyette et al. 2012, Supplemental Data). We used multiple regression analysis to test the pc2fm. Regression coefficients translated the relatively fine-scale units of multiple regression analysis to test the pc2fm. Regression (Guyette et al. 2012, Supplemental Data).

**Climate Data**

Currently the pc2FM utilizes three covariates of MFI: 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 et al. 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 MFIc (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) that 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 (MFI) 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 determination, 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 (r² > 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.
Comparing modeled mean fire intervals (MIF) to 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, $\text{PTR}$) of fire frequency to increased precipitation in fuel-limited ecosystems. Conversely, a negative response (increased fuel moisture and humidity, $\text{AR}$) 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 km²) 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.

Acknowledgments

The authors wish to thank Cody Winks, Jeff Sparks, Gary Willson, Ralph Godfrey, Tom Bragg, Daniel C. Dey, the staff of Theodore Roosevelt National Park, and the owner of Lazy S B Ranch for their aid and cooperation throughout this study’s extensive fieldwork. This study was supported by the National Park Service, the Great Plains Cooperative Ecosystem Studies Unit, the USGS, the University of Missouri’s Forestry Department, and the Missouri Tree Ring Laboratory.

References


Climate Dynamics and Fire Frequency • Richard P. Guyette et al. 149

Forest Service, Intermountain Research Station, Fire Sciences Laboratory, Missoula MT.


