THESIS

CHARACTERISTICS OF WILDFIRE-IGNITING LIGHTNING IN THE WESTERN UNITED STATES

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ABSTRACT

CHARACTERISTICS OF WILDFIRE-IGNITING LIGHTNING IN THE WESTERN UNITED STATES

Annually, over half the wildfires on federal lands in the conterminous western United States are caused by lightning. However, broad-scale characteristics of wildfire-igniting lightning flashes are poorly understood, and limit our ability to predict what role climate change might have on lightning patterns and in turn on future patterns of wildfire. I investigated lightning-wildfire relationships by comparing the characteristics of lightning flashes that start fires to those that do not across 29 ecoregions in the western US from 2003-2007. After accounting for ecoregional variation, I found little meaningful difference in characteristics of igniting flashes including the proportion of positive flashes, proportion of negative flashes with long continuing current, number of strokes per flash (multiplier), or flash peak current (all attributes thought to be related to ignition potential). In contrast, I found that wildfires are associated with significantly higher lightning flash densities near fire locations compared to further away. However, the role of flash density varied significantly between ecoregions. Given the non-uniqueness of igniting flashes, simple proxies such as storm frequency or intensity may be sufficient to estimate likelihood of lightning ignitions under changing climatic conditions. However, these estimates must be mediated based on ecosystem response to potential ignitions.

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TABLE OF CONTENTS

ABSTRACT ii

ACKNOWLEDGEMENTS iii

TABLE OF CONTENTS iv

LIST OF TABLES vi

LIST OF FIGURES vii

CHAPTER 1: OVERVIEW 1

Lightning background 4

Lightning detection 7

Wildfire background 9

CHAPTER 2: ATTRIBUTES OF LIGHTNING FLASHES 13

Introduction 13

Methods 14

Fire database 14

Lightning flash selection 15

Assignment of flashes to fires. 16

Ecoregions subsets 18

Analysis 18

Results 22

Overall fire-lightning relationships 22

Spatial and temporal characteristics 24

Lightning characteristics of source pool 27

Lightning characteristics from fire perspective 28
Discussion 30
CHAPTER 3: DENSITY OF LIGHTNING FLASHES 33
Introduction 33
Methods 34
Data 34
Analysis 35
Results 37
Overall fire-lightning relationships. 37
Lightning density by period and proximity. 37
Lightning density and ecoregion relationships 38
Quantile relationships 39
Discussion 42
CHAPTER 4: IMPLICATIONS FOR FUTURE WILDFIRE PATTERNS 45
Introduction 45
Methods 46
Results 47
Discussion 48
REFERENCES 50

LIST OF TABLES

Table 1: Locational Accuracy (LA) and Detection Efficiency (DE) of the NLDN....................... 8

Table 2: Summary of changes in NLDN sensitivity and capability, 1990-2008........................... 8

Table 3: Ecoregions and fires in the conterminous western US and study area, 2003-2007....... 19

Table 4: Flash composition in analysis area by ecoregion at fire locations................................. 25

Table 5: Mean (95% confidence interval) flash density at natural fire locations within ecoregions by temporal period.. 40

Table 6: Lower quartile (95% confidence interval) of pooled fire period flash density and upper quartile of off-fire period flash density by ecoregion.. 41

LIST OF FIGURES

Figure 1: Data model for fire and lightning records. 3

Figure 2: Nomenclature for locational accuracy.. 9

Figure 3: Map of fire density by ignition type 11

Figure 4: Schematic of flash and fire temporal and spatial relationships 17

Figure 5: Koppen climate zones and EPA ecoregions used in text 21

Figure 6: Flash patterns by ecoregion 23

Figure 7: Difference from western US mean percent positive flashes by ecoregion.................... 24

Figure 8: Difference from western US mean percent negative flashes by ecoregion................. 26

Figure 9: Difference from western US mean positive amplitude based on peak current of the first stroke by ecoregion 28

Figure 10: Difference from western US mean positive multiplier by ecoregion......................... 29

Figure 11: Difference from western US mean negative long continuing current multiplier by ecoregion 30

Figure 12: Correlation of characteristics... 31

Figure 13: Broad-scale fire and flash density by ecoregion 38

Figure 14: Flash and stroke density at lightning-caused fire locations across the western US during 2003-2007 39

Figure 15: Mean and threshold flash densities (flashes/km2 5-days) at fire locations by ecoregion 42

Figure 16: Percent increase in potential wildfire ignitions 49

CHAPTER 1: OVERVIEW

Lightning flashes are responsible for over half the wildfires started each year in the conterminous western United States accounting for more than 75% of burned area (National Interagency Fire Center [NIFC] 2015). More than 2 million hectares (Mha) burn each year (NIFC 2015) with 1.6 Mha due to lightning-caused fires. Government fire fighting costs now exceed US$1 billion/year, approaching US$2 billion in 2012. Over the past 25 years, both wildfire number and burned area have increased across the western United States (hereafter "western US") (Pechony and Shindell 2010). This increase has been attributed to climate change with the trend expected to continue given projections for warmer and drier conditions and increased lightning frequency (Pechony and Shindell 2010, Romps et al. 2014, and Stravros et al. 2014).

Climate prediction models have begun to provide sufficient resolution to enable the estimation of future lightning events in the face of global warming (see for example Romps et al. 2014). These estimates are typically of a general nature, e.g. that lightning will increase by some percentage under given assumptions. Translating an increase in lightning to an increase in wildfires requires insight into the relationship of lightning flashes and wildfire ignitions. While it is obvious that wildfires are started by lightning, the role (if any) of specific flash characteristics in ignition is less well understood. Simply put, more lightning may or may not mean more wildfires, particularly if the additional lightning fails to have critical attributes. Even though climate change influences on patterns of wildfire are contingent on lightning regimes, currently a lack of understanding of specific lightning-wildfire relationships limits the ability to determine how this contingency might play a role in shaping climate influences on wildfire regimes

(Bowman et al. 2011). Past researchers were limited to in their ability to explore these influences due to the aggregated nature of available lightning data, lacking an ability to evaluate characteristics of individual flashes. Within the last twenty years, lightning detection systems have become available that record attributes of individual flashes enabling the exploration of specific lightning flash attributes (Cummins and Murphy 2009). It is now realistic to consider the role of individual flashes in wildfire ignitions.

The research presented here examines two questions about the relationship of lightning flashes and wildfires. First, are all flashes equally likely to generate ignitions? If not, what aspect(s) of a lightning flash best characterize ignition potential. Second, is lightning equally likely to generate ignitions across all landscapes? If not, what are the relationships between lightning flashes and ignitions across landscapes. The results of the research into these questions are then used to estimate changes in natural wildfire ignitions based on predicted changes in lightning frequency with projected climate change. A conceptual model (fig. 1) provided a framework for integrating the research questions and data exploration.

This research is part of a larger framework to address questions regarding the role of anthropogenic ignitions in pre-history and the role of natural and anthropogenic ignitions in a warmer, drier western US. Specifically, if a correspondence of natural ignitions to fire numbers can be demonstrated, then assuming no change in the natural ignition frequency, any excess of fires in the fire record are likely due to anthropogenic causes, even in the absence of direct evidence of ignition source. In the western US, natural fires are almost exclusively caused by lightning with a relatively small contribution (if any) from volcanic eruption, meteor impact, or underground coal seam fires. Modern anthropogenic wildfires are the result of prescribed burning, arson, accidental campfire escape, sparks from automobile catalytic converters and

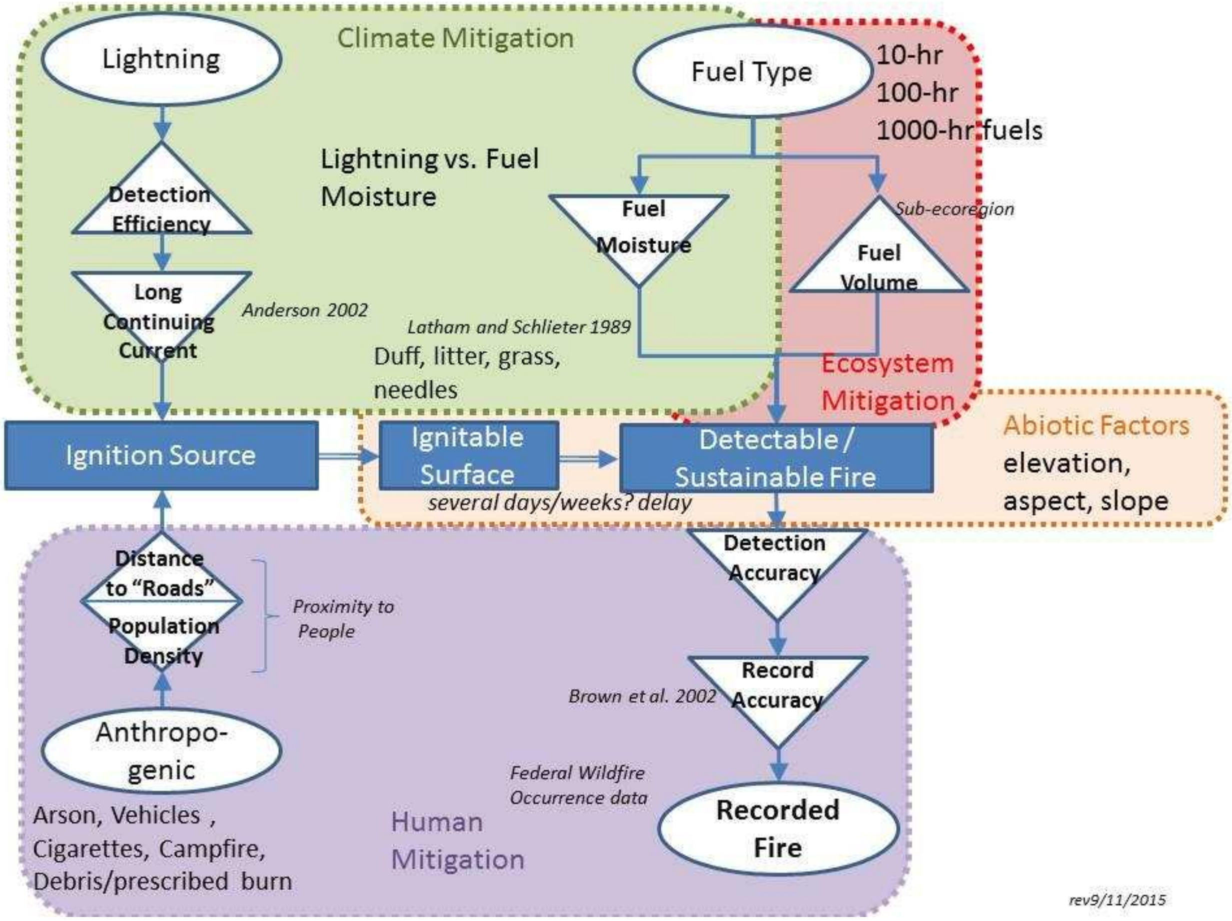

Figure 1: Data model for fire and lightning records.

railroad cars, unextinguished cigarettes, and other intentional and unintentional human activities (USDA, FS FireStats User's Guide 2003). Before the modern era, anthropogenic fires were likely the result of a combination of accidental cooking fire escape and deliberate burning to clear undergrowth and, in grasslands, stimulate fresh growth to attract grazing animals (although the role of these fires in landscape modification is unknown see Stewart 2002, Vale 2002). The extent of fire spread and severity regardless of ignition source is a function of available fuels, fuel moisture, and local weather conditions (Keane 2015, Parks et al. 2014, Parisen et al. 2012, Littell et al. 2009). Fuels must be flammable, sufficiently dry, and continuous enough with sufficient wind to promote fire spread for an ignition to result in a spreading fire. Fuels and fire spread are well addressed in the literature and thus the current research focuses strictly on natural ignitions, a comparatively less well-understood aspect of wildfire.

This thesis is comprised of four chapters. This introduction, which provides a background of lightning and wildfire, two research chapters each investigating an aspect of lightning and wildfire, and a final chapter, which explores the implications for wildfire ignitions, based on climate change predictions of lightning frequency. Chapter 2 examines the attributes of flashes, specifically polarity, amplitude, and multiplier and their role in ignitions. Chapter 3 examines the role of flash density in wildfire ignition in light of the findings regarding flash characteristics. Chapter 4 applies the results of chapters 2 and 3 to project wildfire increases attributable to increases in lightning as a result of predicted climate change.

Lightning background

Lightning is created by the transfer or "discharge" of electrical charge from atmospheric clouds to another location. When this location is the ground, the lightning is "cloud-to-ground" (CG); when within (intra-cloud or IC) or between clouds, it is "cloud-to-cloud" (CC). CC lightning can initiate anywhere within the cloud. In contrast, CG discharges usually initiate from the lower (closest to ground) cloud layers. When the lower layer is negatively charged, the lightning produced is "negative"; when positively charged, the lightning is positive. Most commonly, lower layers are negatively charged with the balancing positive charge areas located higher in the cloud. This configuration is flipped during winter storms, very strong storms (i.e. convective thunderstorms on the Great Plains and tornados [see for example Fleenor et al. 2009]), and possibly in storms over salt water. Lightning occurs when the accumulated charge exceeds the breakdown potential of the surrounding matrix (air). The charge is conducted to ground (or a ground surrogate such as trees, towers, buildings) via a channel about 2.5-5 centimeters in diameter (Rakov and Uman 2003:Table 1.1). The channel may be used for the return stroke (serving to rebalance the excess charge at the ground surface, the return stroke is what is usually seen by observers, measured, and recorded), by subsequent strokes (a "multistroke" flash), or may simply sustain for 100s of milliseconds (ms) continuing to drain charge from the cloud. When this sustaining current is longer than 40 ms, the discharge is said to have a "long continuing current" (LCC, Brook et al. 1962, Kitagawa et al. 1962). Typical duration of a return stroke is ~ 3 ms (Rakov and Uman 2003:176).

A flash is a collection of strokes that have similar origination points and that occur within close proximity in time (within ms). As mentioned above, subsequent strokes may use an existing channel but this in not always the case. Due to cloud movement and discharge dynamics, strokes (particularly positive strokes) from the same flash may strike the ground at locations separated by 10s of kilometers (Saba et al. 2010). A flash is typically characterized as positive or negative based on the polarity of the first stroke. The lightning detection system (discussed below) in place for the data used in the research presented here reported first stroke polarity as flash polarity, multiplier (the number of strokes per flash), and first stroke peak current (kiloamperes, kA) as flash peak current. More recently the system reports individual stroke detail.

Positive and negative strokes have several different properties. Negative flashes are more common and are most usually multistroke (multiplier~2.5; Orville et al. 2011:Fig. 7). Positive flashes represent about 10% of all flashes (but this varies by geographic location, season, storm lifecycle, and storm type [Rakov and Uman 2003:4, 217]) and are usually single stroke (multiplicity ~1.5 [Orville et al. 2011:Fig. 8; 1.2, Saba et al. 2010]). The absolute median peak current for negative and positive flashes is similar, around 23-30 kA but the means are different due to more extreme currents in positive strokes (~200kA compared to ~80 kA in negative strokes [Rakov and Uman 2003:219]). Of importance to fire initiation (see below), almost all positive strokes have a continuing current and of these most have LCC associated with them regardless of peak current value. In contrast, single stroke negative flashes rarely have LCCs. When LCC's occur in negative flashes they occur on a subsequent stroke. In addition, negative flashes with high peak currents do not have LCC (Saba et al. 2010). Recent fieldwork has found that LCC flashes occur more frequently in the decaying phase of thunderstorms (Saraiva et al. 2010a)

Across the US, mean flash density ranges from approximately 0 (Alaska and the Pacific Coast) up to more than 9 flashes/kilometers^2 year (km^2 yr) (Florida and Gulf Coast [Orville et al. 2011:Fig. 2]). Positive flashes account for anywhere from 1% (Southwest and Rockies, Eastern Appalachians and seaboard) to 15% (central to northern Great Plains) of flashes (Orville et al. 2011:Fig. 4). Negative flash median peak current is typically -12 to -18 kA across the US; positive median peak current varies regionally with highest currents (>25 kA) in the Pacific Northwest, the western Great Plains and the California Coast and most of the western US outside of the Southwest [Orville et al. 2011:Fig. 6]). Seasonally, positive lightning can be as little as 6-7% of flashes during summer (June-July-Aug) and as high as 20% in winter (Nov-Dec-Jan-Feb [Orville and Huffines 1999:Fig. 5]). After large wildfires in Mexico in early spring 1998, Lyons et al. (1998) reported a significant increase in the percentage of positive CG flashes (from 13.7% to 40% during the peak period) and the average peak current of lightning (from 27 kA to 42 kA) across the Great Plains. They speculated that the additional particulate in the smoke altered the electrical properties of storms.

Lightning detection

While lightning flashes can have many attributes only a small number are collected for every flash and recorded by the National Lightning Detection Network (NLDN) operated by Vaisala Corp. The NLDN was originally established to monitor lightning hazards and consequently most early effort was directed at rapid detection of flash presence (Cummins et al. 1998, Cummins and Murphy 2009). More than 100 sensors across the US detect and report lightning occurrence in near real time (Cummins et al. 2006). Since the initial operation of the system in the 1990s, improvements have been made to flash detection, measurement of peak current, locational determination, and separation of cloud-to-ground (CG) and cloud-to-cloud (CC) flashes (tables 1 and 2). In 2002, the system went through a major sensor upgrade that, among other things, improved locational accuracy to roughly 0.5 km (the semi-major axis of a 50% confidence ellipse, fig. 2) and detection accuracy to about 92%. In 2008, another system upgrade vastly improved algorithms (Koshak et al. 2015) and in 2013 all sensors across the US were again updated including improved processing algorithms (Nag et al. 2014). Between 2003 and 2007 the system, though not as precise as today's system, remained relatively stable.

Like the fire data set, lightning records are not without their limitations. First, detection efficiency although improving through time is still less than 100% so all flashes are not recorded. In particular, flash detection for positive flashes may be even lower, possibly as low as 60-70%. Second, locational accuracy is still relatively large, about 0.5 km making assignment of a specific flash to a specific ignition point difficult in lightning-rich storms. Third, the system uses algorithms to extract CG strokes from all strokes (CC and CG); this is based on a probabilistic assumption relating current and duration to likelihood of a flash being either CG or CC so some types of each flash are potentially misclassified. For comparison, over 80% of flashes are CC

Table 1: Locational Accuracy (LA) and Detection Efficiency (DE) of the NLDN.

Year	LA 50% Semimajor axis, km	LA 95% Semimajor axis, km	DE % of flashes	Peak current underestimation, %
1989*	4-8	8-16	70	
1990	4-8	8-16	70	
1991	4-8	8-16	70	
1992	2-4	4-8	65-80	
1993	2-4	4-8	65-80	
1994	2-4+++	4-8	65-80	
1995	0.5-1	1-2	80-90	18
2003**	0.282-0.424		92-93	
2004***	0.308		92	13
2010****	0.436		100 %	15
2004-2013+	0.309		94	14
2014 ++	0.200 (estimate)			

* 1989-1995, Cummins et al. 1998:Table 1, DE is for peak current >5 kA
** Biagi et al. 2007
*** Nag et al. 2011
**** Mallick et al. 2012, note that sample size was 23.
+ Mallick et al. 2014 based on 92 lightning flashes triggered by rocket launches from Camp Blanding, FL
++ Nag et al. 2014
+++ Note however that Bureau of Land Management sensors were upgraded in 1994 so western US results are likely more typical of US wide 1995 performance

Table 2: Summary of changes in NLDN sensitivity and capability, 1990-2008.

	1990-1991	1992-1993	1994-2002	2003-2005	2006-2008
Potential positive CC threshold	5 kA*	5 kA*	10 kA	10 kA	15 kA**
Potential negative CC threshold	-5 kA***	-5 kA	-5 kA	- 5 kA	-5 kA

* assumes that prior to the 1994 upgrade, the system sensitivity was low enough that only CG were detected even though the threshold was at 5 kA.
** System cutoff effective April 2006
Citations follow table 1.

(Nag et al. 2014). Fourth, the system also uses an algorithm to assign single strokes to clusters defined as flashes and in the past only information about the earliest stroke in the cluster was reported (newer data reports full information). Consequently, information about stroke position within a flash is not available in earlier records. Fifth, although peak current is reported, there is

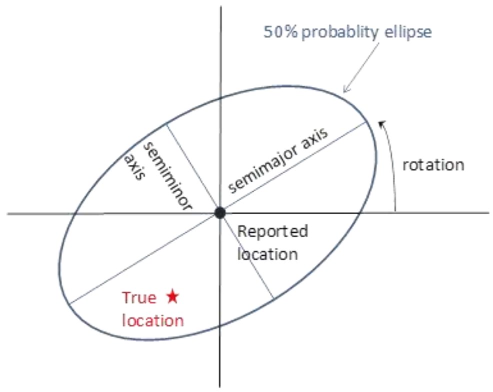

Figure 2: Nomenclature for locational accuracy. By convention, there is a 50% probability that the true location of the lightning stroke falls within the ellipse described by the semi-major and semi-minor axes and rotation. Axes lengths and rotation are dependent upon the location of the reporting sensors with respect to the stroke.

only weak correlation between peak current and total energy level (see below). Again, like the fire dataset, the temporal and spatial extent of the lightning dataset makes it the only data source available to examine individual flashes. Other large extent databases such as NASA's (2015) Lightning Imaging Sensor/Optical Transient Detector (LIS/OTD) Climatology data sets consist of gridded total flash rates and thus provide only aggregated data over time or space. Finally, there are good validation methods of the detection system for negative flash determinations using ground-launched rockets to create flashes (see for example, Nag et al. 2011, Jerauld et al. 2005) and high-speed video recording of natural flashes (Saraiva et al. 2010, Saba et al. 2006a). However, because of the difficulty in artificially generating positive flashes, only high-speed videography coupled with electronic filed measurements are available for validation of natural positive flashes (Saba et al. 2010). Videography/field measurement allows for the evaluation of flash duration, current, and multiplier but not of locational accuracy or detection efficiency.

Wildfire background

Wildfires are the result of the combination fuel, oxygen, and heat referred to as the "fire triangle" (Moritz et al. 2005). This triangle has different controls over different scales of time and space. At the smallest scale, flames can be a few meters in extent and last a few seconds and fire is driven by the availability of fuel, oxygen, and heat (Moritz et al. 2005:Fig. 1). At regional scale, fire regime (typical time between fires, fire severity, and fire size [Baker 2009:Table 5.1]) is controlled by available ignitions, vegetation type, and climate patterns. At medium scales, wildfires are governed by local weather, topography, and fuels. Ignition sources can be natural or anthropogenic (fig. 3) with anthropogenic fires being driven by proximity to human usage (Syphard et al. 2007).

Wildfires can occur on both public and private lands and may be responded to and recorded by a number of different agencies ranging from private citizens to the federal government. As a result there is no single repository of wildfire information across the United States. The federal government, however, maintains a wildfire database (US Federal Wildland Fire Occurrence database 2014) containing records of fires reported on federal lands or responded to by federal agencies since 1980. This data was deemed sufficient for the current research for several reasons: 1) the US government manages vast portions of the non-urban western US where wildfires occur (fig. 3); 2) fire data has been recorded since the 1970s and while early records are less reliable, data collection practices have improved over time; 3) records include fire location, estimated start date and have been attributed with fire cause; and 4) all fires regardless of size are included. This dataset is not without its limitations, however. First, it is limited to fires that are reported (fig. 1). To be reported a fire needs first to be detected which is more likely near populated areas and access points to less populated areas. The dataset thus underrepresents small fires in remote areas, fires that are very small, quickly extinguished, and/or that occur during the night or on overcast days when smoke or flame visibility is low and observers may not be present. Second, fire start times are reported times and may not accurately

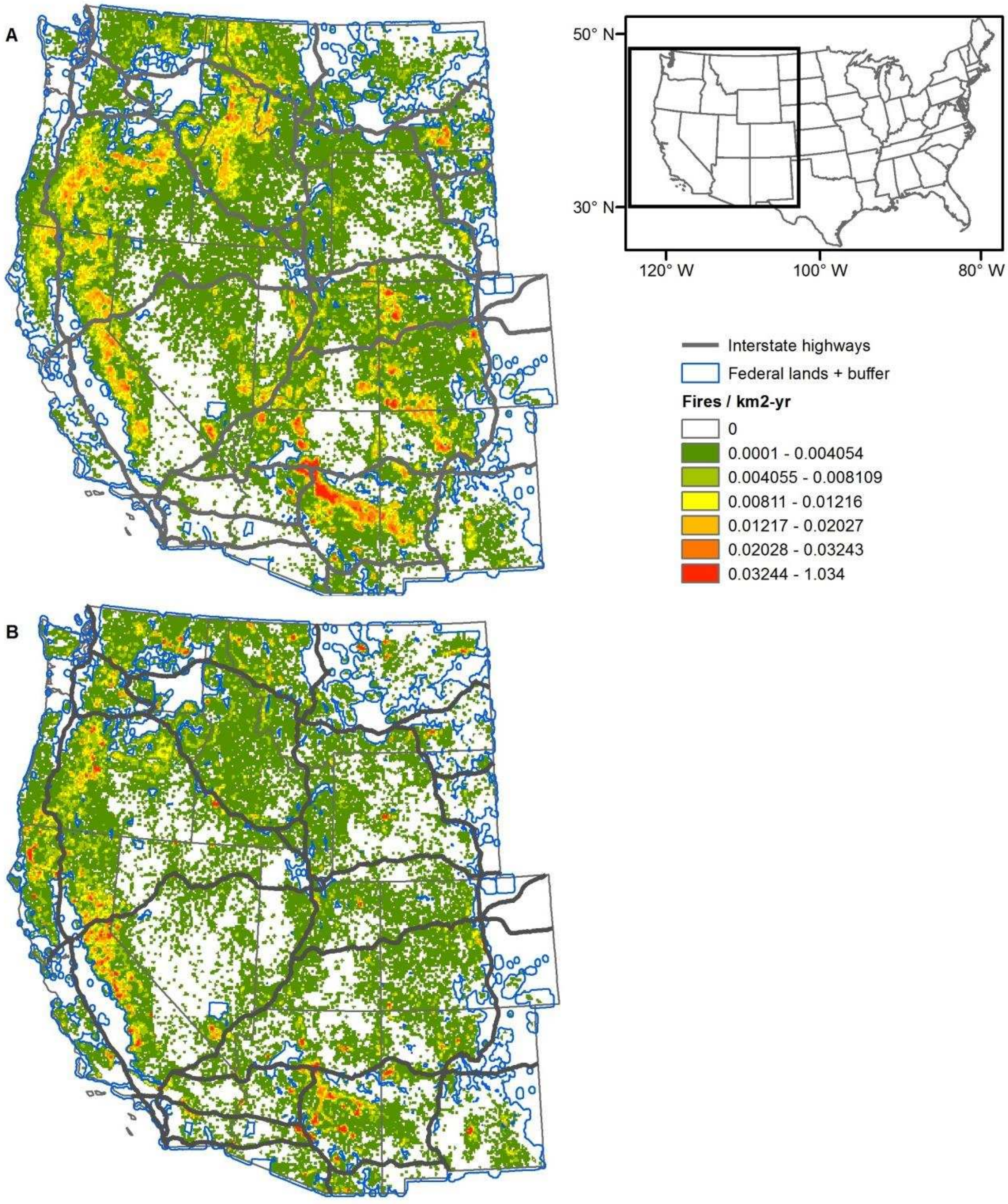

Figure 3: Map of fire density by ignition type: (A) natural and (B) anthropogenic from 1980-2013. Blue lines enclose federal lands buffered by 10-km. For reference, major interstate highways are shown in grey.

reflect ignition times (which may be unknowable) and these reported times are reported to the day not hour or minute. Third, reported fire locations, particularly for large fires, are unlikely to be an accurate indication of ignition location as evidence of actual start location may be lost to subsequent burning, fire suppression activities, or lack of investigation. Finally, given the long temporal record of the dataset, the bottoms up nature of data entry, and the multiple agencies and personnel involved, there are inevitably errors of data entry, duplications, omissions, and so forth (Brown et al. 2002). Even with these limitations, this dataset is the most complete and comprehensive data available for fires in the western US.

CHAPTER 2: ATTRIBUTES OF LIGHTNING FLASHES

Introduction

Although 2-3 million lightning flashes occur in the western US annually (~1 flash/km^2 yr), lightning-ignited fires are relatively rare (~10,000/yr). Various flash characteristics including polarity, energy, and number of strokes per flash (or "multiplicity"); have been suggested to be critical in starting wildfires. Laboratory and field observations have concluded that lightning strokes must have long continuing current components (LCC, an energy transfer duration of at least 40 milliseconds [ms]) to ignite wildfires regardless of polarity or current [Latham and Williams 2001, Latham and Schielter 1989)]. Most strokes with positive polarity (discharging positive charge buildup from cloud to ground [Dwyer and Uman 2014]) have LCC. Early researcher (Flannigan and Wotton 1991), however, found that most fires were started by negative flashes. More recent field research has suggested that only negative flashes with multiple strokes and with first stroke peak current between 0 and -20 kiloamperes (kA) contain LCC (Pineda et al. 2014, Saba et al. 2006a) thus limiting which negative flashes could be important in wildfires ignition. Storm formation properties may also be important to the generation of flashes with ignition potential. Generally over the western US, overall flash density is highest in the afternoon (Holle 2014: Fig 9). Negative flash activity increases and peak current magnitude decreases during the afternoon and evening periods compared to either mornings or nighttime (Chronis et al. 2015). Positive flashes often originate in the upper portion of clouds and during high-energy storms (Lang et al. 2004, Rakov and Uman 2003).

Understanding the role these patterns have in generating potentially igniting flashes is critical to envisioning how altered characteristics of lightning might shape patterns of wildfire in a warming world. If, for instance, positive flashes are key to wildfire ignitions, then an increase in high energy storms is more relevant to fire prediction than a simple increase in storms overall.

Here, five years (2003-2007) of spatially and temporally explicit records of lightning flashes and wildfires were used to investigate lightning-wildfire relationships on federal lands in the western US. The study tested whether the occurrence of LCC flashes (either positive or negative) was different at fire locations based on percentage of these flashes and flash multiplicity (number of strokes per flash). This study also tested whether the peak current of positive flashes was higher at fire locations.

Methods

Fire database

US Federal Wildland Fire Occurrence database (see Chapter 1) was used as the source for fire locations on federal lands west of about -102° exclusive of Alaska, Hawaii, and coastal islands (fig. 3) between 2003-2007 to match the lightning dataset (see next paragraph). A boundary layer of federal lands circa 2008 buffered by 10-km used to delimit the extent of the study area. Fires on Fish and Wildlife Service lands are frequently recurrent prescribed burns to maintain open habitat, particularly wetland habitats and consequently were excluded. Where possible, duplicate (or multiple agency reports) records were deleted. Records lacking a start date, location (latitude/longitude), or cause other than "natural" were also removed. Locational accuracy and the precise ignition location for the fires were unknown. However, the majority of fires (97%) were reported at less than 100 acres, limiting potentially large locational errors. Reported fire date was taken as the ignition date recognizing the potential for inaccuracy due to smoldering periods and detection and reporting delays. All recorded ignitions were included regardless of resulting fire size, severity, or duration recognizing that these post-ignition properties depend upon on fuel characteristics and weather conditions (Keane 2015, Parks et al. 2014, Parisen et al. 2012, Littell et al. 2009), as well as fire suppression efforts.

Lightning flash selection

While lightning flashes can provide an ignition source, actual ignition only occurs at locations with flammable materials, e.g. combustible fuels with sufficiently low fuel moisture and proximity to additional fuels to promote fire spread. Consequently, the lightning dataset was limited to locations within 5-km of reported fires to control for flammability. Lightning flash records from the NLDN (see Chapter 1) were used that included a date stamp (year, month, day, hour, min, sec in UTC [Coordinated Universal Time] time), latitude and longitude, multiplier (the number of strokes assigned to each flash), and the signed peak current in kiloamperes (kA) of the first stroke. Locational accuracy and detection efficiency from 2003-2007 were roughly 0.4 km (table 1, 50% semi-major ellipse axis) and 92%, respectively (Nag et al. 2011). During this period sensors and algorithms for the NLDN were relatively stable (Koshak et al. 2015) compared to a period of significant sensor upgrades prior to 2003 and algorithm changes beginning in 2008. Following Cummins et al. (2006) and Biagi et al. (2007), only positive flashes with currents greater than 10 kA were retained and all negative flashes less than -5 kA were retained as being most likely to be cloud-to-ground (CG) flashes for this analysis. The practice of Brook et al. (1962) and Kitagawa et al. (1962) was followed by defining LCC as flashes with duration of at least 40 ms. Since continuing current was not reported, a negative LCC flash was defined as any negative flash with initial peak current between -20 kA and -5 kA (Saraiva et al. 2010b: Fig. 11). Negative flashes with large peak current tend not to have LCC so were eliminated by the -20 kA cutoff (Saraiva et al. 2010b, Saba et al. 2006b). There is some indication that the likelihood of LCC is also contingent upon the stroke position within negative flashes with fewer LCC strokes on first strokes of multi-stroke flashes and in single-stroke flashes (Medeiros and Saba 2012, Saraiva et al. 2010b, Saba et al. 2006a, 2006b). Lacking information on within-flash strokes, no adjustment for stroke position was made. Although the likelihood of LCC in low-current, single-stroke negative flashes has been estimated at only 15%, no adjustment for single-stroke flashes was made as there was no mechanism to isolate which flashes comprised this portion (Medeiros and Saba 2012). Pineda et al. (2014) and Saba et al. (2010b) found LCC at all values of initial peak current in positive flashes, consequently all positive cloud-to-ground flashes were assumed to have LCC. Although the likelihood of LCC is weakly correlated with peak current, it was assumed that all flashes within the defined current cutoffs had 100% likelihood of LCC. While these assumptions likely overestimate the number of LCC flashes, collectively they provide an upper bound on the overall proportion of LCC flashes.

Assignment of flashes to fires.

Due to uncertainties in both fire and flash locations in time and space, the identity of the specific igniting flash for each fire could not be determined. Instead, a candidate pool of flashes at each fire location was identified. This pool was comprised of all flashes that occurred within a 5-km radius and 3 days prior to, on the day of, and one day following the fire (fig. 4). The 5-day window accounted for offsets of fire date (in local time) and lightning time stamp (in UTC), smoldering, and reporting delays of evening and nighttime ignitions. In Australia (Dowdy and Mills 2012) and Finland (Larjavaara et al. 2005), fires were visually detected within 2-3 days of ignition. Fires in the North American boreal forest were remotely sensed within 3 days of ignition (Peterson et al. 2010). Additionally, dry lightning storms in the western US typically last from 1 to 3 days (Nauslar 2014). The 5-km window allowed for errors in both lightning and fire locations while minimizing the inclusion of non-storm area based on a thunderstorm extent of

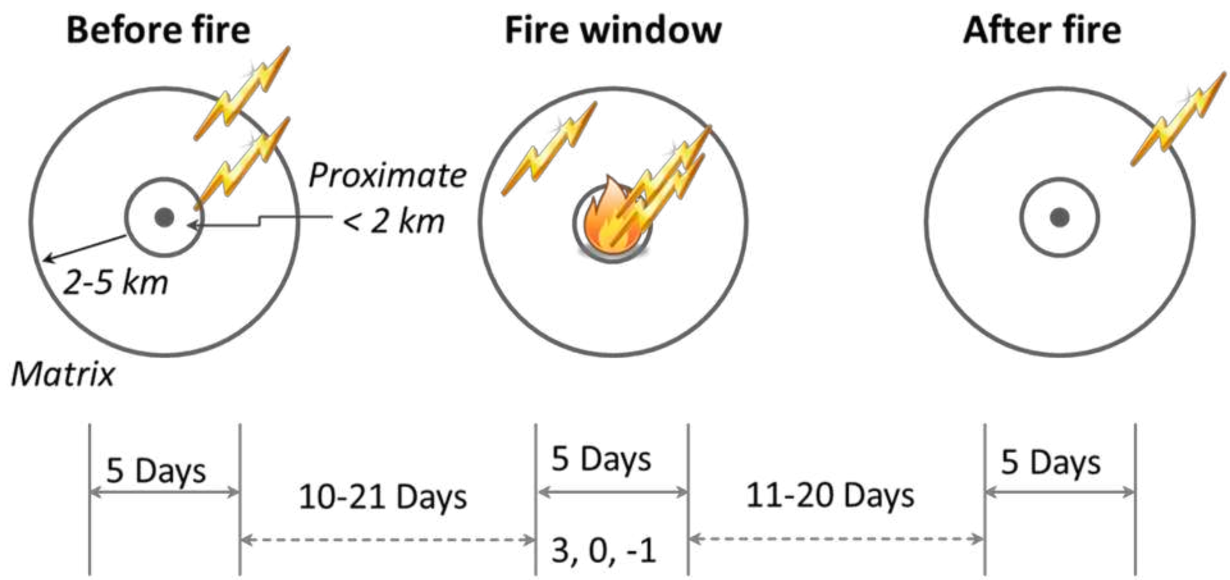

Figure 4: Schematic of flash and fire temporal and spatial relationships. The recorded location of each fire provided a center point for each observation location. Around that location two distance intervals: proximate, within 2-km of the center, and matrix, between 2 and 5-km away were defined. At each observation location, all lightning that occurred during any of three sampling time periods (Before fire, Fire window, and After fire) were assigned to the location. The Fire window was a 5-day interval surrounding the recorded start date of the fire, commencing 3 days prior to the fire and including one day after the fire start. The Before fire time period was comprised of a 5-day interval randomly determined to start from 10 to 21 days prior to the recorded start date of the fire. Similarly, the After fire period was a 5-day interval randomly assigned to start 11 to 20 days after the recorded start date of the fire.

roughly 5-10 km (Price and Rind 1994a). Local topographic barriers to lightning flashes being able to reach a given fire location were ignored. This assignment of flashes to fire locations meant that some flashes were potentially assigned to fire locations after the fire started or that a flash could not physically reach. It also meant that due to detection inefficiencies, locational errors, and long smoldering times, some fires were not assigned any flashes even if they were lightning caused. Additionally, a fire location could have multiple flashes assigned to it and a flash could be assigned to multiple fire locations.

To test differences between lightning characteristics when fires occurred and when they did not, all flashes occurring at each fire location during two random 5-day intervals starting 10-

21 days before and 11-20 days after the fire (fig. 4) were identified. Temporal changes in fuels and fuel moisture were minimized by limiting the off-fire periods to a few weeks either side of the fire start date. Given the limited locational accuracy of both lightning and fires, only flashes within 2-km of fire locations were considered likely to be responsible for ignitions. Flashes 2-5 km away from fire locations were deemed part of the same lightning storm but comprised a pool of non-igniting lightning.

Ecoregions subsets

Fires and flashes were stratified using US Environmental Protection Agency Level 3 ecoregions (US Environmental Protection Agency [EPA] 2015) on federal lands (table 3). To minimize edge effects, only the largest contiguous area of each ecoregion was used, discarding small areas outside the main area. In addition, fire locations that fell within 5-km of an ecoregion boundary were deleted (however, flashes within this area were retained if associated with a fire location interior to the 5-km buffer). Ecoregions with very small numbers of fires and small federal areas ecoregions were discarded (fig. 5, table 4 footnote). Twenty-nine ecoregions were retained. Although ecosystems within ecoregions are highly diverse, the study assumed wildfire-relevant differences, most specifically climate, among ecoregions were larger than within (fig. 5, EPA 2014).

Analysis

Lightning characteristics were considered from two perspectives. First, lightning flashes were analyzed from the cloud or source perspective (ecoregion scale) and second from the fire location perspective (local scale). The first perspective investigated attributes of the lightning source pool by examining characteristics of individual flashes. This precluded the association of a given flash with any particular fire location since a flash could simultaneously be near multiple

Table 3: Ecoregions and fires in the conterminous western US and study area, 2003-2007.

		Western US			Study area				
ID	Ecoregion name*	Area, km^2	Total Fires	Flashes / km^2 yr	Area, km^2	Natural	Human	Total Fires	Natural Fires /km^2 yr
1	Coast Range	19,769	820	0.034	11,321	155	97	252	0.0045
4	Cascades	42,493	2,914	0.127	32,293	851	757	1,611	0.0100
5	Sierra Nevada	52,546	5,469	0.260	41,220	2,036	2,180	4,235	0.0205
6	Central California Foothills and Coastal Mountains	22,075	2,654	0.055	13,702	15	195	210	0.0031
9	Eastern Cascades Slopes and Foothills	52,241	2,977	0.299	29,693	1,239	565	1,807	0.0122
10	Columbia Plateau	17,882	875	0.113	12,105	17	269	294	0.0049
11	Blue Mountains	68,291	3,547	0.284	55,255	2,268	938	3,214	0.0116
12	Snake River Plain	50,474	1,187	0.248	31,116	183	593	845	0.0054
13	Central Basin and Range	302,739	5,901	0.587	275,530	3,708	1,101	4,863	0.0035
14	Mojave Basin and Range	123,205	2,649	0.670	106,366	907	1,047	2,079	0.0039
15	Northern Rockies	75,564	4,122	0.273	62,001	1,958	1,306	3,337	0.0108
16	Idaho Batholith	60,279	3,124	0.377	52,187	2,404	353	2,771	0.0106
17	Middle Rockies	131,058	3,203	0.733	107,796	1,362	677	2,072	0.0038
18	Wyoming Basin	132,053	1,436	0.909	114,666	761	352	1,196	0.0021
19	Wasatch and Uinta Mountains	42,997	1,882	1.340	29,709	759	199	964	0.0065
20	Colorado Plateaus	136,387	6,736	1.453	117,444	4,669	686	5,471	0.0093
21	Southern Rockies	126,710	5,172	2.009	99,377	2,731	998	3,823	0.0077
22	Arizona/New Mexico Plateau	133,343	2,698	1.883	86,720	331	884	1,245	0.0029
23	Arizona/New Mexico Mountains	80,621	9,673	3.267	61,693	5,476	1,566	7,102	0.0230
24	Chihuahuan Deserts	76,300	485	2.153	45,282	34	37	72	0.0003
26	Southwestern Tablelands	29,746	124	2.497	18,344	22	30	57	0.0006
41	Canadian Rockies	18,880	592	0.362	13,486	285	116	405	0.0060
42	Northwestern Glaciated Plains	38,563	1,769	0.821	30,583	86	939	1,052	0.0069
43	Northwestern Great Plains	139,452	2,500	1.286	106,033	1,237	949	2,260	0.0043
77	North Cascades	27,701	782	0.094	22,640	382	286	670	0.0059
78	Klamath Mountains/California High North Coast Range	47,423	4,544	0.114	37,517	1,212	2,727	4,002	0.0213

Table 3 (continued): Ecoregions and fires in the conterminous western US and study area, 2003-2007.

		Western US			Study area				
ID	Ecoregion name*	Area, km2	Total Fires	Flashes / km2 yr	Area, km2	Natural	Human	Total Fires	Natural Fires /km2 yr
79	Madrean Archipelago	32,765	767	3.485	22,766	224	285	531	0.0047
80	Northern Basin and Range	138,816	1,851	0.357	116,732	953	386	1,394	0.0024
81	Sonoran Basin and Range	112,045	4,618	1.215	89,863	109	2,091	2,362	0.0053
Total (% = Analysis/Western US)		2,332,417	85,071		1,843,436 (79%)	36,374 (60%)	22,609 (38%)	60,196 (71%)	
	Average	80,428	2,933	0.942	63,567	1,254	780	2,076	0.0074
	Minimum	17,882	124	0.034	11,321	15	30	57	0.0003
	Maximum	302,739	9,673	3.485	275,530	5,476	2,727	7,102	0.0230

Notes: The following western US EPA Level III ecosystems were dropped from analysis: Central California Valley, 73 fires; Southern California Mountains 29,000 fires but less than 10,000 km^2 of managed area; Southern California/Northern Baja Coast 4,000 fires but less than 10,000 km^2 in contiguous managed area; High Pains, 600 fires; Puget Lowlands, 17 fires; and Willamette Valley, 161 fires).

fire locations. The second perspective controlled for between location effects by treating each fire location and all lightning flashes within a 5-km radius as a single observation. In this treatment, a given flash could be included in multiple observations and consequently assumptions of independence were violated.

At the ecoregion scale, flash characteristics of percentage of positive and negative LCC flashes of total flashes, positive flash peak current, and multiplier by time period (before, during, or after fire) and fire proximity (within 2-km or 2-5 km from the fire) were evaluated based on the relationship of each unique flash to the closest fire in space and/or time. Current was not evaluated for negative LCC flashes since the values were limited by constraining LCC flashes to -5 - -20 kA. To determine between ecoregion differences, mean attribute values by ecoregion and flash type were calculated. This study followed the lightning science field's practice of reporting mean peak current (see for example Koshak et al. 2015). To validate this practice, skewed

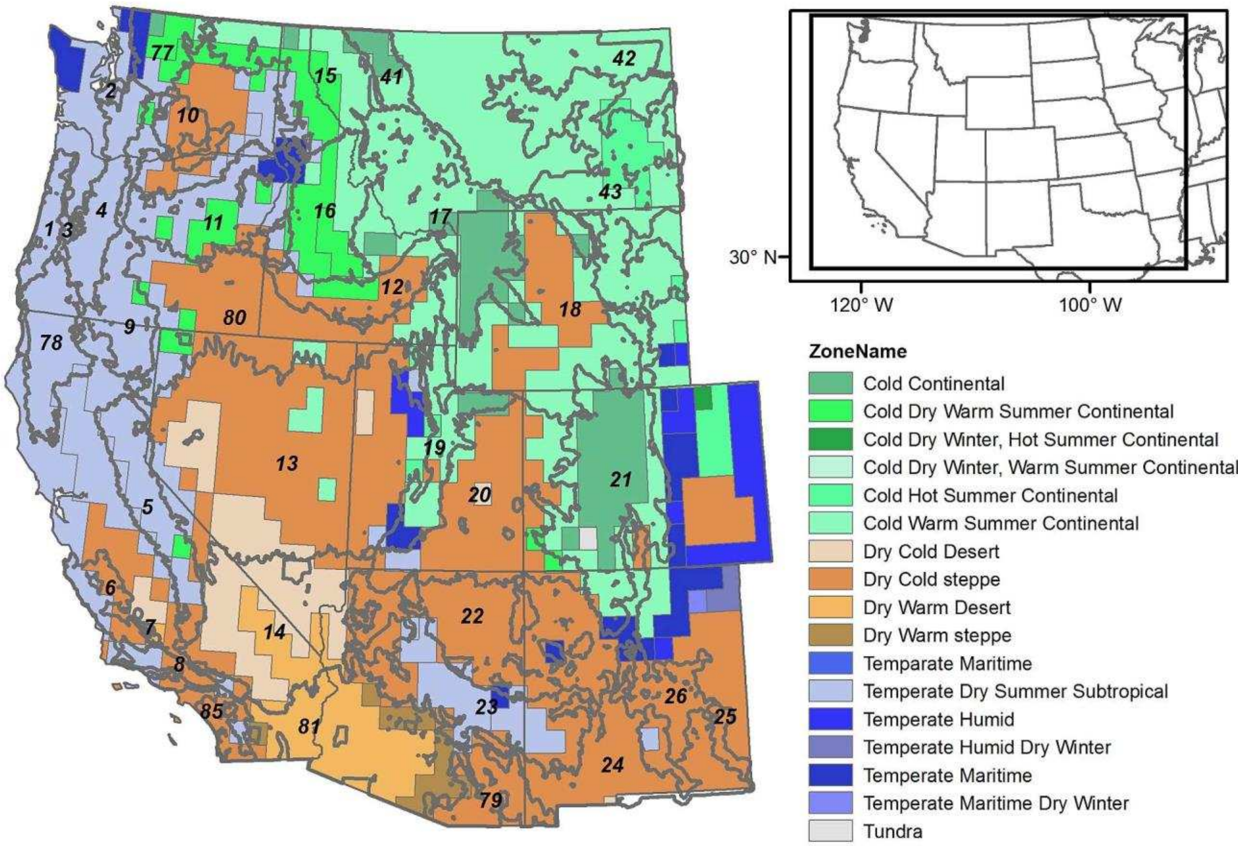

Figure 5: Koppen climate zones(FAO 2013) and EPA ecoregions (US EPA 2015) used in text. Numbers refer to table 3 ecoregion ID listings.

distributions of positive amplitude and multipliers were analyzed using both untransformed and natural logarithm transformed data and results compared. A mixed linear model was used to compare time period and proximity relationships treating ecoregion and ecoregion interactions as random effects using SAS MIXED procedure (SAS 2002-2010). Least square means with Tukey adjustment for multiple comparisons are reported. A general linear model was used to compare means across ecosystems (SAS GLM procedure) using a Nelson-Hu adjustment for multiple comparisons. For multiplier comparisons, McDonald and White (2010) was followed and used normal regression rather than Poisson regression or a data transform as counts were small and truncated (<15).

At the local scale, flash characteristics of polarity, peak current, and multiplier were evaluated at each fire location where lightning was present during all three temporal windows. Using fire location as the observation unit, paired differences between distances during each time period at each location were determined for these values and then tested for whether any of the mean paired differences were different from 0 and different from each other within ecoregion using a mixed linear model (MIXED procedure [SAS 2002-2010]). Ecoregion and ecoregion interactions were treated as random effects and Tukey adjusted least squares estimates for mean differences at the ecoregion level are reported.

Results

Overall fire-lightning relationships

Roughly 85,000 fires occurred on 2.3 Mkm^2 of managed federal lands in the western US during 2003-2007 (table 3). Seventy-one percent (60,200) of these occurred in the study area ecoregion blocks (79% of the western US area, fig. 6A). Lightning was reported as the cause for 60% (36,375) of fires, humans caused 38% (22,610), and the reminder had unknown origin.

Roughly 720,000 lightning flashes occurred within 5-km of fire locations. Overall positive flash percentage was 4%. Positive flash percentage varied by ecoregion (figs. 6C and 7, table 4) with highest percentages in the Snake River Plain [ecoregion ID 12] (12.3% [8.7-16.0%, 95% confidence interval]) and Sierra Nevada Mountains [5] (8.7% [7.7-9.6%]). Lowest percentages were in the Colorado Plateau [20] (2.9% [2.5-3.4%]). Overall negative LCC flash percentage was 65% and varied between ecoregions (figs. 6E and 8). Highest levels of negative LCC were found in the Mojave Basin [14] (72.0% [70.7-73.6%]) and Sonoran Basin [81] (70.1% [67.3-72.8%]); lowest levels in the Coast Range [1] (31.0% [18.1-43.4%]).

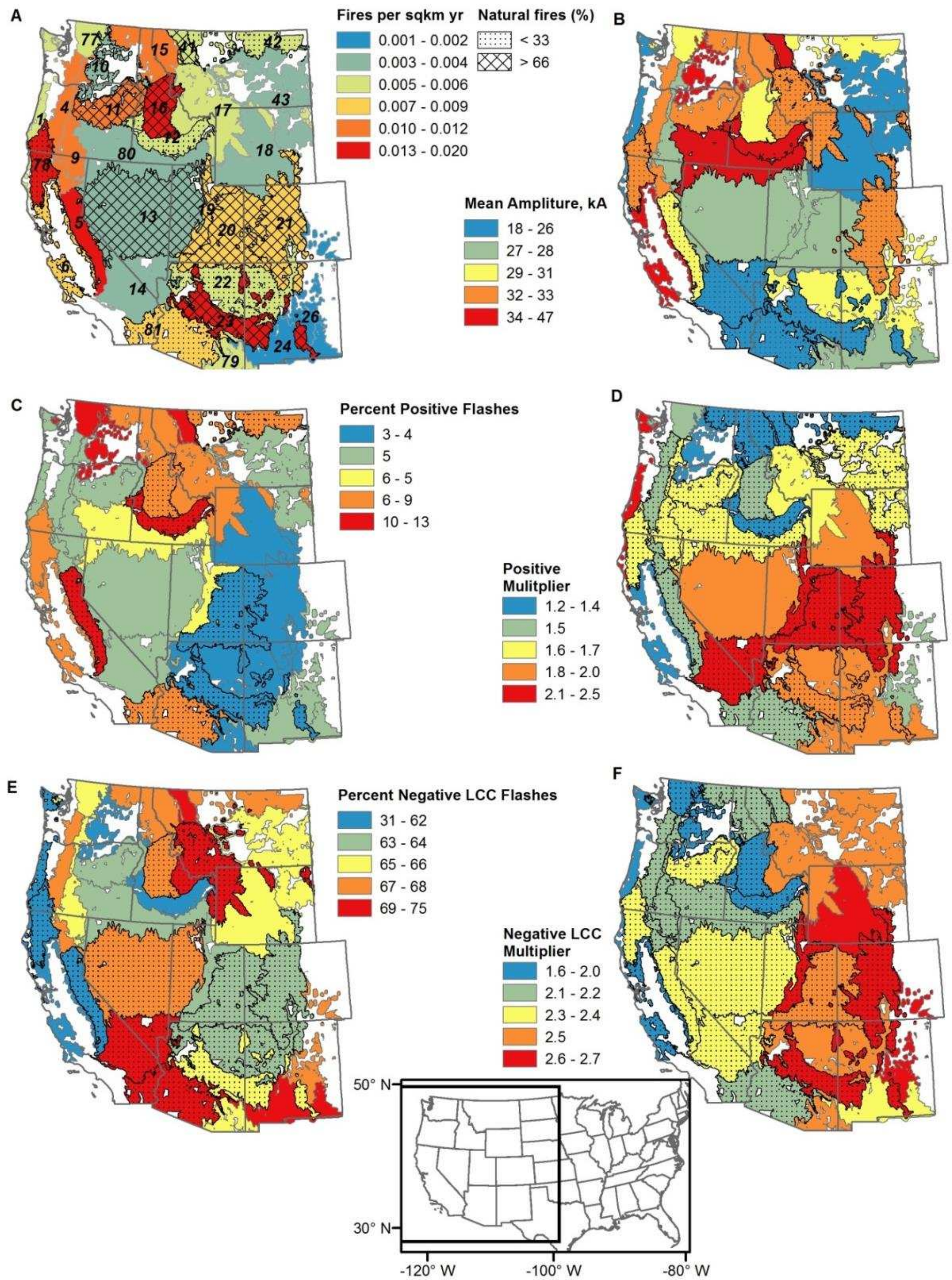

Figure 6: Flash patterns by ecoregion. (A) Natural fire density (number of fires attributed to lightning flashes per 100 km^2 yr^1). (B) Mean peak current of positive flashes by ecoregion. Overall mean = 28.5 kA. (C) Percentage of positive flashes. (D) Multiplier (strokes per flash) of positive flashes. (E) Percent of negative long continuing current flashes (LCC). (F) Mean peak current of negative flashes with long continuing current (LCC). Overall mean = 2.5. In panel, stipple/hatching indicates natural fire percentage. In panels B-F, stipple indicates ecoregions where value is significantly different from the overall mean (p<0.05). Ecoregion names and attribute values shown in tables 3 and 4.

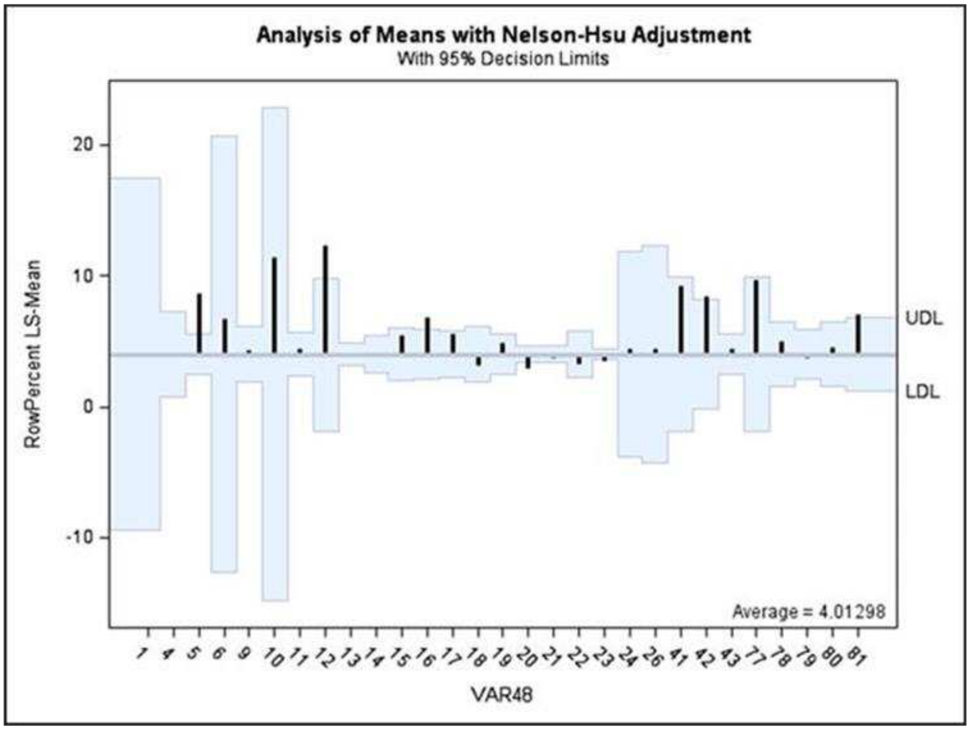

Figure 7: Difference from western US mean percent positive flashes by ecoregion. Shading indicates 95% confidence interval of a zero difference. Ecoregions are as listed in table 3.

Spatial and temporal characteristics

Based on the assumption that igniting flashes occurred within 5 days and 2-km of fire locations, there were 124,400 potentially igniting flashes. Only 4,000 positive flashes occurred within 2-km and 5 days of fires and these occurred near 9,500 fires. Of these, 643 fires had only positive lightning nearby. Percentage of positive flashes was significantly lower within 5 days of fires than either before or after (4.7 %, compared to7.0% [-2.7 - -1.7, Tukey adjusted 95% confidence interval of difference], p<0.0001) and but did not differ by proximity to fire. Roughly 24,900 positive flashes occurred further from fire locations in time or space and did not start fires.

In comparison, roughly 78,000 negative LCC flashes occurred close to 28,000 fires. Of these fires, 19,174 had no positive lightning nearby. As with positive flashes, many (390,000) negative LCC flashes occurred further from fire locations in time or space reflecting the role of

Table 4: Flash composition in analysis area by ecoregion at fire locations.

ID	Ecoregion name	Polarity, %		Peak Current,	Multiplier	
		Pos.	Neg. LCC	Pos. kA	Pos.	Neg. LCC
1	Coast Range	4	31*	18	2.5	1.9
4	Cascades	4	67	31	1.4	2.0
5	Sierra Nevada	9*	62*	31*	1.4*	2.2
6	Central California Foothills and Coastal Mountains	7	43	47	1.2	1.6
9	Eastern Cascades Slopes and Foothills	4	64	28	1.5*	2.2
10	Columbia Plateau	11	56	42	1.3	1.7
11	Blue Mountains	4	64	31	1.5*	2.4
12	Snake River Plain	12*	58	39*	1.4*	1.9
13	Central Basin and Range	4	68*	27	1.9	2.3
14	Mojave Basin and Range	4	72*	24*	2.1*	2.2
15	Northern Rockies	5	68	31	1.4*	2.1
16	Idaho Batholith	7*	68*	30	1.4*	2.0
17	Middle Rockies	6	68*	32*	1.7	2.5
18	Wyoming Basin	3	66	26	2.0	2.5
19	Wasatch and Uinta Mountains	5	63	28	2.2*	2.6
20	Colorado Plateaus	3*	62*	28	2.0*	2.4
21	Southern Rockies	4	63*	32*	2.1*	2.6
22	Arizona/New Mexico Plateau	3	62*	30	1.8	2.4
23	Arizona/New Mexico Mountains	4*	66*	26*	2.0*	2.7
24	Chihuahuan Deserts	4	75	28	2.0	2.3
26	Southwestern Tablelands	4	68	29	1.4	2.6
41	Canadian Rockies	9	68	36*	1.3*	2.1
42	Northwestern Glaciated Plains	8*	66	30	1.2*	2.5
43	Northwestern Great Plains	4	65	26	1.5*	2.5
77	North Cascades	10	65	30	1.4	1.8
78	Klamath Mountains/California High North Coast Range	5	56*	33*	1.5*	2.2
79	Madrean Archipelago	4	65	28	1.7	2.5
80	Northern Basin and Range	5	64	34*	1.5*	2.2
81	Sonoran Basin and Range	7*	70*	24*	1.5*	2.0
	Mean	4	63	29	1.6	2.2
	Minimum	3	31	18	1.2	1.6
	Maximum	12	75	47	2.5	2.7

Notes: Pos., Positive; Neg. LCC, Negative Long Continuing Current.
*, significantly different from the overall mean ($p<0.05$)

other factors such as fuel moisture in mediating actual ignition given an ignition source. The percentage of negative LCC flashes was also lower during the 5-day fire window than either before or after (62.2% compared to 64.9 [-4.0 - -1.4, Tukey adjusted 95% confidence interval of

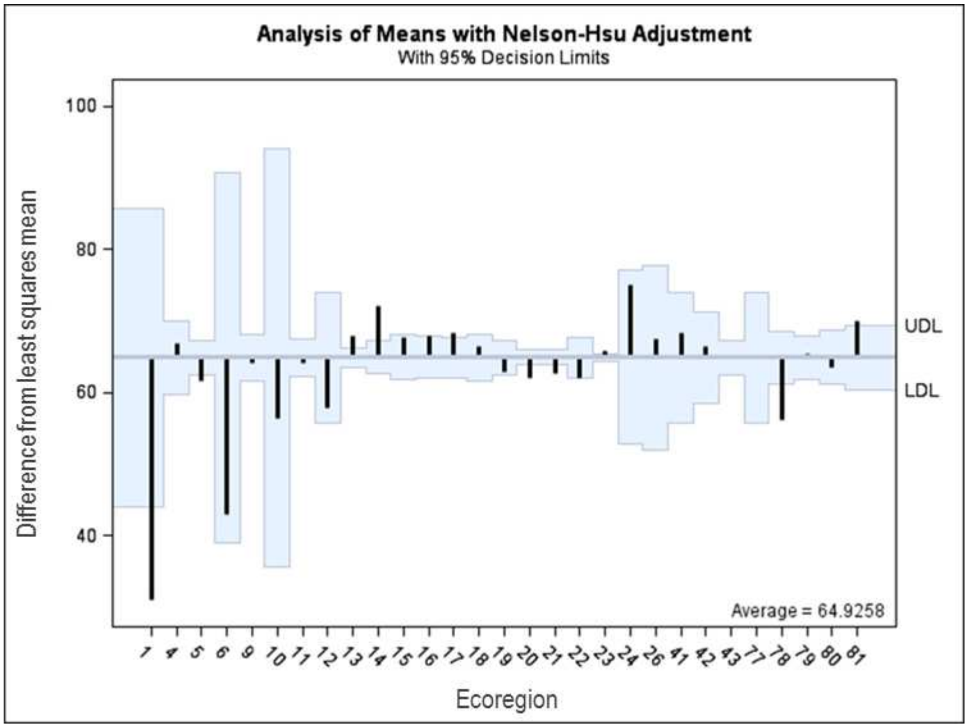

Figure 8: Difference from western US mean percent negative flashes by ecoregion. Shading indicates 95% confidence interval of a zero difference. Ecoregions3 are as listed in table 3. LDL and UDL are Upper and Lower decision limits (equivalent to 95% upper and lower confidence limits on the difference from the overall least squares mean).

difference], p<0.0001). During the 5-day fire window, negative LCC flash levels were higher at a distance of 2-5 km from the fire than closer to the fire (63.6% compared 60.9% [0.7-2.2], p<0.0006).

About 4% (1,522) of natural fires had only non-LCC negative lightning nearby. This finding was not unexpected given the very rough proxy of multiplier and peak current for the presence of long continuing current. Ten percent (3,600) of fire locations had no lightning during the fire window but did have lightning either before or after. The failure to record lightning during the fire window may be due to locational inaccuracies for fire and lightning locations, lightning detection error, smoldering periods greater than three days, or attribution error. Roughly 7% (2,500) of reported natural fires had no lightning before, during, or after the fire window at any distance. Given the scarcity of lightning at these locations, the original attribution of lightning cause was likely incorrect.

In summary, positive lightning was responsible for roughly 2% of ignitions (643/36,375), negative LCC lightning to be responsible for 53% of ignitions (19,174) and either positive or negative LCC flashes responsible for 24% (8,900). Roughly 14% (5,100) of fires had no lightning at all or no positive or no negative LCC flashes within 5-km.

Lightning characteristics of source pool

Examining the roughly 29,000 positive flashes within 5-km of fire locations during all three periods, mean positive peak current during the fire period (28.9 kA) was slightly but significantly lower than either the before or after periods (31.1 kA [-2.7 - 0.6 kA, Tukey adjusted 95% confidence interval of mean difference] and 30.5 kA [-3.5 - -1.0] p <0.0003, respectively). Peak positive current did not vary based on distance to fire location. There were significant differences in mean positive peak current by ecoregion (overall mean 28.5 kA, ranging from 18-47 kA, table 4, figs. 6B and 9). Analysis of natural logarithm transformed amplitude yielded similar results. There was a small but significant increase in positive multipler during the fire period (1.7) compared to the before period (1.5 [0.04-0.23 Tukey adjusted 95% confidence interval of mean difference], p<0.0015) but not the after period (p>0.09) or proximity. Positive multiplier varied by ecoregion (table 4, fig. 6D and 10).

Examining multiplier of the 467,526 negative LCC flashes within 5-km of fire locations during all three periods, there were statistically significant differences both by period and by proximity to fire location. However, the overall range of these differences was small: smallest multiplier: before fires within 2-km, 2.1 (2.02-2.26), compared to largest multiplier: within 5

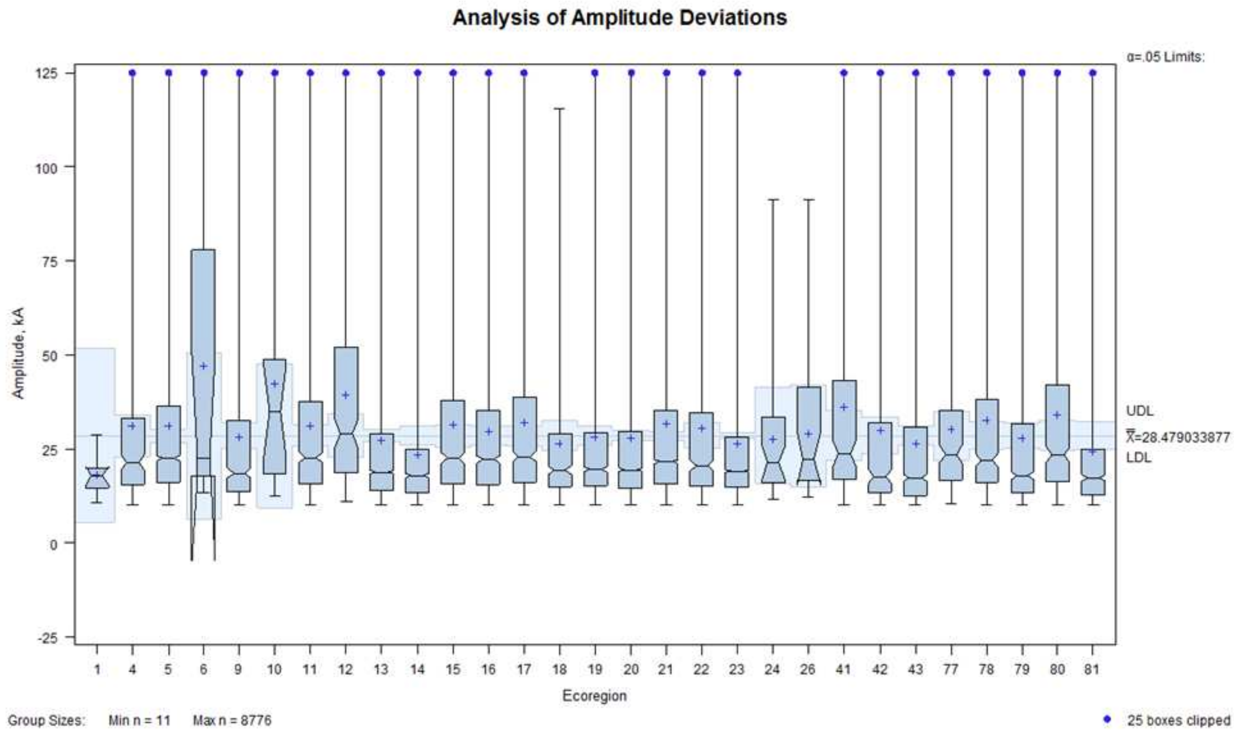

Figure 9: Difference from western US mean positive amplitude based on peak current of the first stroke by ecoregion. Shading indicates 95% confidence interval of a zero difference. Ecoregions are as listed in table 3. LDL and UDL are Upper and Lower decision limits (equivalent to 95% upper and lower confidence limits on the difference from the overall least squares mean).

days of fire and within 2-km: 2.3 (2.22-2.43) with an estimated adjusted difference of 0.08-0.297 (table 4, figs. 6F and 11).

None of these characteristics (polarity percent, current, or multiplier) was strongly correlated with the occurrence of natural fires (note the lack of pattern matching across panels A and B-F in fig. 6, correlation plots provided in fig. 12).

Lightning characteristics from fire perspective

When positive lightning was present (at 3,173 locations), on average there were 1.3 positive flashes within 2-km (range 1-21). There was no difference in positive flash percentage based on proximity to fires or ecoregion (n = 26,922 fire locations with lightning during fire period, 5,574 locations with lightning before the fire, and 7,531 locations with lightning after the

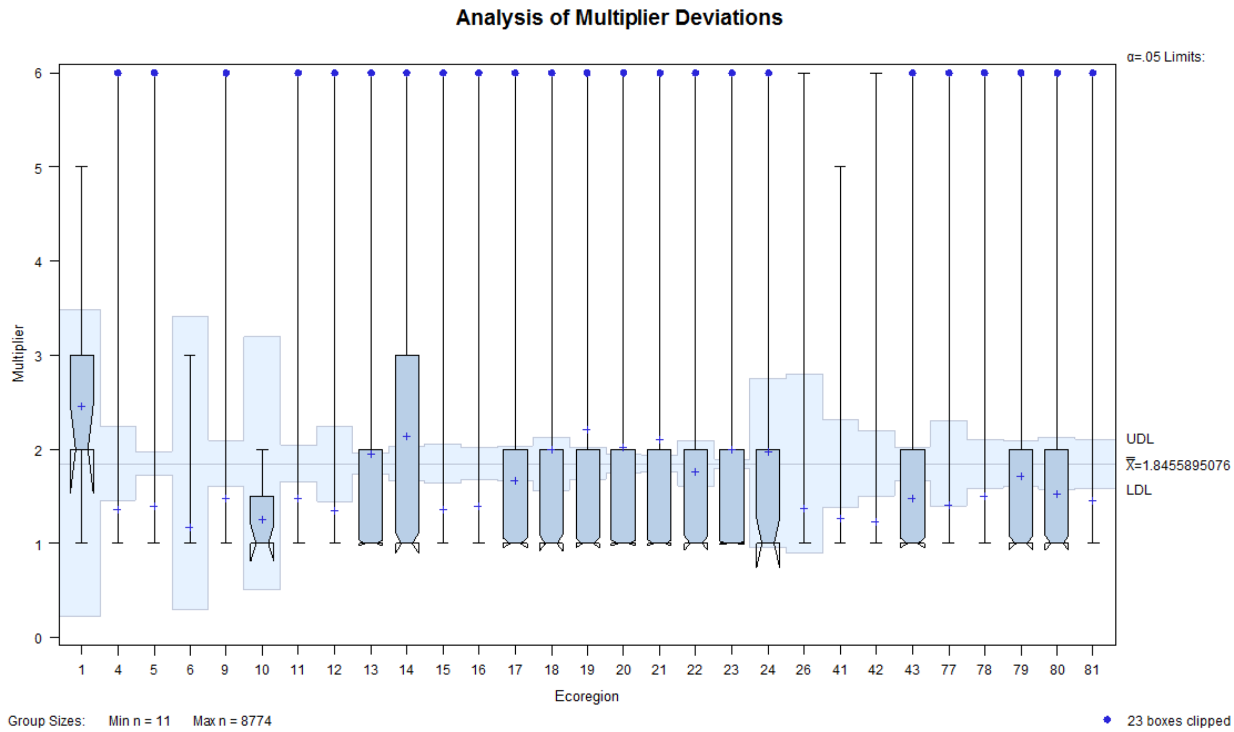

Figure 10: Difference from western US mean positive multiplier by ecoregion. Shading indicates 95% confidence interval of a zero difference. Ecoregions are as listed in table 3. LDL and UDL are Upper and Lower decision limits (equivalent to 95% upper and lower confidence limits on the difference from the overall least squares mean).

fire p>0.2). There was a significant decrease in positive flash percentage during the fire window (6%) compared to both before and after (9.8% [-4.4 - -2.8%, Tukey adjusted 95% confidence interval], p<0.0001) Positive polarity percentage was not significantly different between before and after periods. Similar to the source pool results, there was a slightly lower percentage of negative LCC flashes within 2-km of fires during the fire (60%), compared to before (64% [-4.0 - -0.6%], p<0.006) fires and no difference in percentage after fires. Mean peak current of positive flashes was significantly lower during the fire period (28 kA) and did not differ between before and after periods (30 kA [-3.2 - -0.8, Tukey adjusted 95% confidence interval], p<0.004) or by nearness to fire location. Multiplier for positive flashes was significantly higher during the fire period (1.8) compared to either before or after (1.6 [0.06-0.31, Tukey adjusted 95% confidence

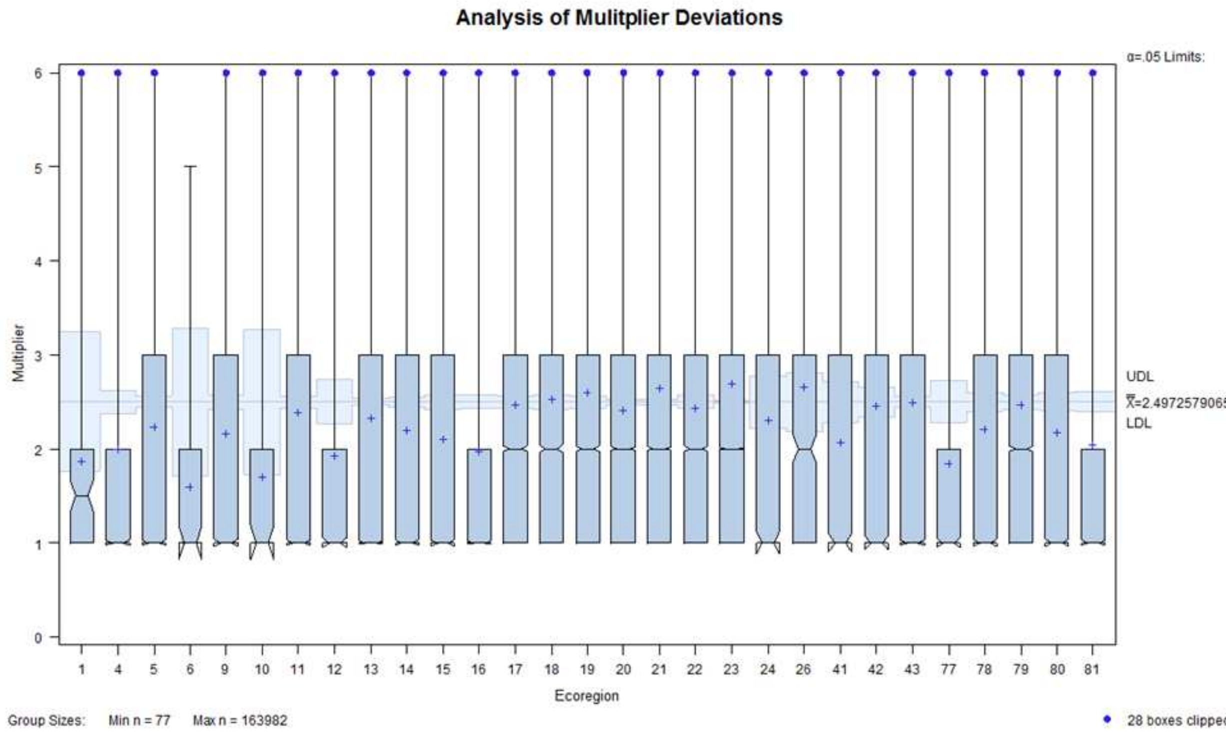

Figure 11: Difference from western US mean negative long continuing current multiplier by ecoregion. Shading indicates 95% confidence interval of a zero difference. Ecoregions are as listed in table 3. LDL and UDL are Upper and Lower decision limits (equivalent to 95% upper and lower confidence limits on the difference from the overall least squares mean).

interval] p<0.005). Multiplier for negative LCC flashes was significantly higher during the fire (2.2) compared to before or after (2 [0.16-2.7], p<0.0001). Multiplier for negative LCC flashes was also significantly higher within 2-km of fires (2.05) compared to further away (1.96 [0.06-0.12], p<0.0001), regardless of time period.

Discussion

These results demonstrate that although positive flashes are capable of igniting fires, they are not the only source of ignition and do not result in ignitions in most cases. This results quantify and extend the findings of Latham and Williams (2001), Flannigan and Wotton (1991), and Hall and Brown (2006) for the role of negative long continuing current flashes as ignition sources. However, the study was not able to examine diurnal patterns to determine if negative

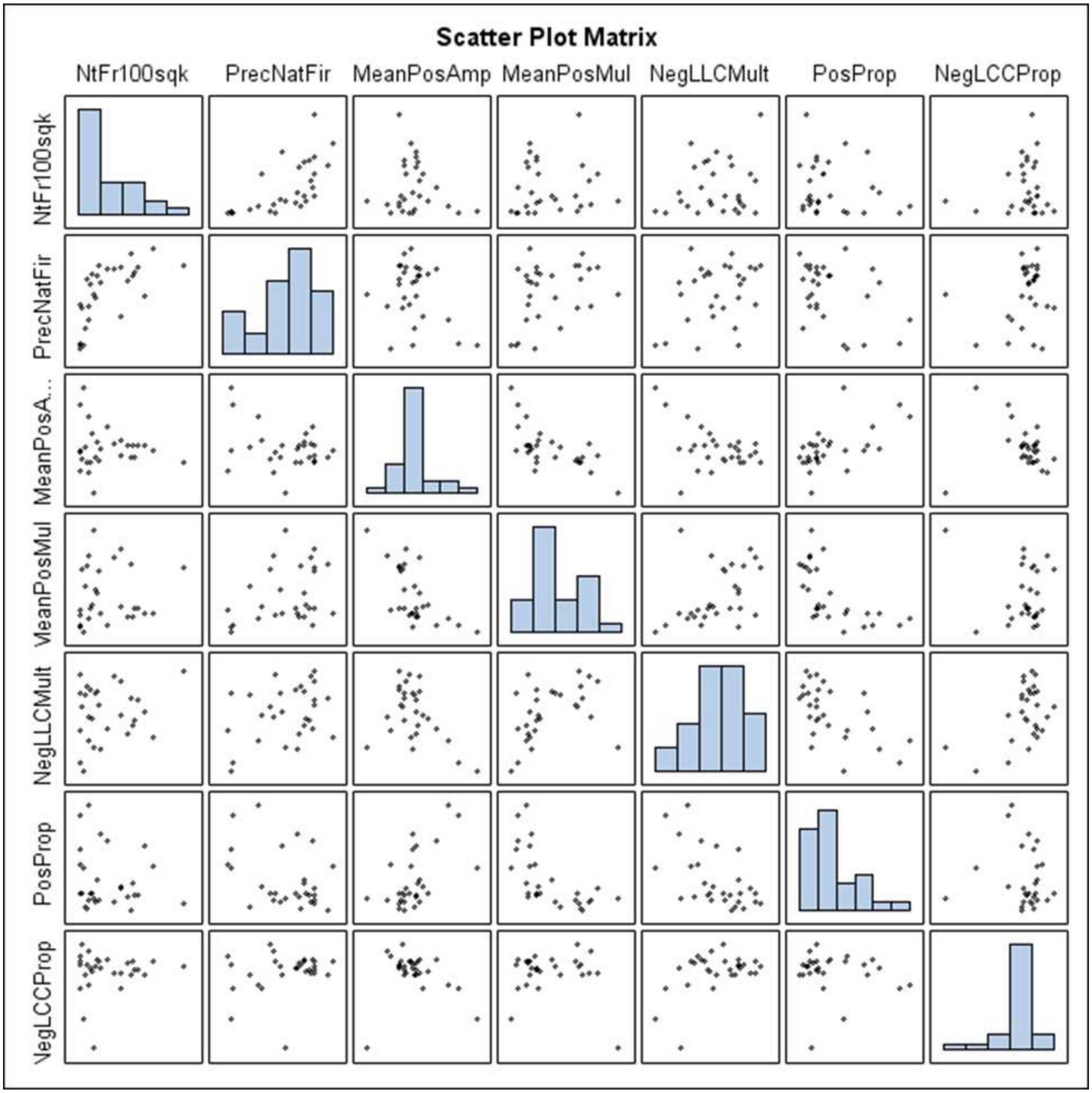

Figure 12: Correlation of characteristics. Correlation of (from left to right, top to bottom) natural fires/100-km2 (NtFr100sqk), percent natural fires (PrecNatFir), mean positive current (MeanPosAmp), mean positive multiplier (MeanPosMul), mean negative LCC multiplier (NegLCCMult), proportion positive flashes (PosProp), and proportion negative LCC flashes (NegLCCProp). Each point represents the average value for an ecosystem (n = 29). Largest Pearson correlation coefficient between mean positive current and mean positive multiplier, ρ = 0.65

long continuing current flashes were more frequent in afternoon storms (Chronis et al. 2015) and consequently more likely to start late day fires. There was support for the role of long continuing current rather than high peak current in ignitions (Latham and Williams 2001, Latham and Schielter 1989) since there was lower peak current in positive flashes closest to fire locations in time and space. Although there was some indication of higher multipliers for both positive and negative LCC flashes near fires during fire periods, these differences were small and likely not ecologically meaningful. At an ecoregion-scale, none of these attributes correlated well with wildfire ignitions suggesting that most lightning storms have the potential to contain igniting flashes and only when these flashes strike suitable materials will a wildfire be initiated.

Further, these results suggest that the lightning formation processes in storms that result in lightning ignitions are not substantially different from non-fire storms across the attributes examined, specifically percentage of positive and negative LCC flashes, multipliers of these flashes, and amplitude of positive flashes. In the context of climate change research, this suggests that proxies for lightning generation such as storm frequency and/or intensity may be appropriate in the absence of other predictors. Recent research suggests that across the US more days will be conducive to severe thunderstorms (Trapp et al. 2007) and lightning flashes could increase by 50% over the next century (Romps et al. 2014). In the western US, however, warmer and drier conditions are expected to reduce the number of convective storms overall while very strong storms will occur more frequently (Del Genio et al. 2007). Of special concern, given the important role of negative long continuing current flashes (roughly 65% of all flashes), is the potential for increased atmospheric aerosols resulting from drier climatic conditions and increased wildfires in the western US (Spracklen et al. 2009) to increase lightning nucleation sites with non-linear changes in lightning formation (Price 2013).

CHAPTER 3: DENSITY OF LIGHTNING FLASHES

Introduction

The previous chapter demonstrated that, broadly speaking, wildfire-igniting lightning flashes are not rare or unique. Instead at least 60% of flashes have the potential to start fires. Another aspect of lightning, density or flashes/unit area/time, has also been identified as a driver of spatial patterns of wildfire at landscape scales (Dilts et al. 2009). There is a significant variation in flash density across the western US (Koshak et al. 2015) which likely contributes to broader patterns of wildfire occurrence. Vegetation communities have co-evolved with climate and to patterns of lightning and consequently it may be an increase in lightning density over background levels rather than density, per se, that contributes to apparent density influences. To investigate this contribution, this study explored how lightning flash density corresponds to the occurrence of wildfires and how (if) this varies by ecoregion. It is hypothesized that, in general, storms with lightning have the potential to start fires but actual ignitions are limited because flashes that contact flammable material are rare. Thus storms with elevated lightning density over background levels (i.e. more ignitions impinging on the landscape) may be required for wildfire ignition. If background levels are typically very low, then any level of lightning could result in fires. In contrast, if background lightning levels are typically high, then very high densities of lightning may need to be present for wildfire ignition. In the first case, there might be an actual threshold value of lightning density that partitions ignition probability. In the second, lightning density is likely to show a monotonic increase from non-ignitions to igniting levels. In the context of climate change, if this hypothesis were true, then increased lightning would be expected to result in non-linear increases in the number of wildfires under projected warming depending upon the ecosystem.

Methods

Data

Five years (2003-2007) of spatially and temporally explicit records of lightning flashes and wildfires were used to investigate lightning-wildfire relationships on federal lands in the western US as described in Chapter 2. While lightning flashes can provide an ignition source, ignition only occurs at locations with flammable materials, e.g. combustible fuels with sufficiently low fuel moisture and proximity to additional fuels to promote fire spread. Consequently, ecosystem analysis was limited to locations within 5-km of reported fires and this distance was partitioned into two bands: within 2-km of the reported ignition location and 2-5 km away. The density of lightning flashes during three 5-day windows: before, during, and after reported fires was examined. Fires were partitioned using 29 US Environmental Protection Agency Level 3 Ecoregions (EPA 2014) to examine ecoregion differences and control for lightning gradients (Koshak et al. 2015). Although ecosystems within ecoregions are highly diverse, differences between ecoregions were assumed larger than within (EPA 2014). All recorded ignitions were considered regardless of fire size or duration. Any ignition has the potential to become a large fire, however, this likelihood is based on fuel characteristics and weather conditions (Parisien et al. 2012, Littell et al. 2009), as well as fire suppression efforts. Because of performance changes in locational accuracy and detection efficiency of the lightning detection system, analysis was limited to the period 2003-2007 (see Chapter 1 and Koshak et al. 2015).

Analysis

For comparison with other studies that have typically reported average lightning density, two simple means were calculated. A broad-scale areal measure of flashes per square kilometer was determined by counting all the flashes within an ecoregion (regardless of proximity to a fire location) during 2003-2005 and dividing by the ecosystem area. A broad-scale measure of flashes per fire was calculated by the simple division of the total number of natural fires in the ecosystem by the total number of flashes.

To determine the effect of ecoregion (e.g. the lightning flash source pool), average flash density values were estimated by ecoregion and flash type (positive or negative LCC) using only flashes within three, 5-day periods and 5-km of natural fire locations. Fire locations that had no observed lightning during all of the periods and at all proximities to fire locations were dropped from the analysis. A mixed linear model was used to estimate mean flash density treating ecoregion and ecoregion interactions as random effects using SAS MIXED procedure (SAS 2003). A general linear model (SAS GLM procedure) was used to evaluate ecosystem-period-location effects. Least square means are reported with Tukey adjustment for multiple comparisons.

At each fire location flash and stroke densities based on multiplier were computed by flash type, fire proximity, and temporal period. Then the paired differences for these values (by proximity and temporal period) was determined by fire location and whether any of the mean paired differences were different from 0 was tested within ecoregion using a mixed linear model. Ecoregion and ecoregion interactions were treated as random effects and Tukey adjusted least squares estimates for mean differences are reported at the ecoregion level. A general linear model (SAS GLM procedure) was used to evaluate ecosystem-period-proximity effects.

From an ecological standpoint, the mean flash density may be a poor indicator of the minimum flash density required for an ignition. Comparison of mean densities between fire and non-fire conditions may also be a poor indicator of the true difference between conditions. To examine this, quantiles were compared. Based on the findings of Chapter 2, that roughly 25% of fire locations had problematic lightning observations (no lightning or no long continuing current flashes within 2-km), a minimum threshold for igniting density was established using the 25% quantile (lower quartile) of density within each ecosystem during the fire period. Correspondingly, during off-fire periods, the 75% quantile (upper quartile) of density was assumed as the ceiling for lightning density not resulting in ignitions. These thresholds accounted for the situation in which other factors limited the occurrence of actual ignition. This condition is often found in ecological settings where quantile regression is used to analyze limiting conditions (see for example, Schmidt et al. 2012, Cade and Noon 2003). Quantiles and 95% confidence intervals were evaluated using SAS procedure QUANTREG (SAS 2002-2010). Off-fire period densities were pooled across distance from fires and period as these were found to be non-significant differences. To improve the intuitiveness of the result, the two distances during the fire period were pooled to create a single fire period density. A distinction of the lower quartile of density during the fire period and the upper quartile of density during other periods, suggests that there is both a minimum threshold of lightning for ignitions and this level of lightning is found only rarely when fires do not also occur. In contrast an overlap of these quantiles suggests the absence of a distinct threshold of increased lightning for ignition and that other controls beyond lightning density govern ignition.

Results

Overall fire-lightning relationships.

Based on total flashes within the study area during 2003-2007, flash densities (flash count per ecosystem area per year) across the study area ranged from 0.03-3.5 flashes/km^2 yr, averaging 0.94 (fig. 13B, table 3). About one-quarter of all flashes fell in the Arizona/New Mexico Mountains [ecoregion ID 23] (fig. 13B). Of particular interest, in areas like the California coast [78] and Sierra Nevada [5], lightning was only detected during the fire period as indicated by low flash to fire ratios (fig. 13C). In these systems, lightning density was low but the occurrence of fires was very high when lightning flashes were present.

Lightning density by period and proximity.

Using fire location as the observation unit, locations recorded anywhere from 0 to 424 flashes within 5-km and across the three periods. Approximately 3,000 locations lacked at least one flash within 5-km during at least one of the periods and were dropped from analysis. When lightning was present during the fire period within 2-km (85% of remaining locations), on average, five flashes occurred (range 1-69, excluding locations with no lightning). During other periods, when lightning was present within 2-km (roughly 20% of locations), on average 4 flashes occurred (range 1-75) within 2-km of fire locations. Considering only the flashes at fire locations, overall, the density of source pool lightning flashes within 2-km of fire locations when fires ignited, regardless of flash attributes or ecoregion, was up to six times higher (0.178 flashes/km^2 5-days, $p<0.0001$, $n = 720{,}000$) than flash densities further from fires and either before or after fires (range 0.042-0.15, fig. 14A). Considering multiplier (stroke count) rather than flashes or using the fire location perspective rather than source pool did not change this

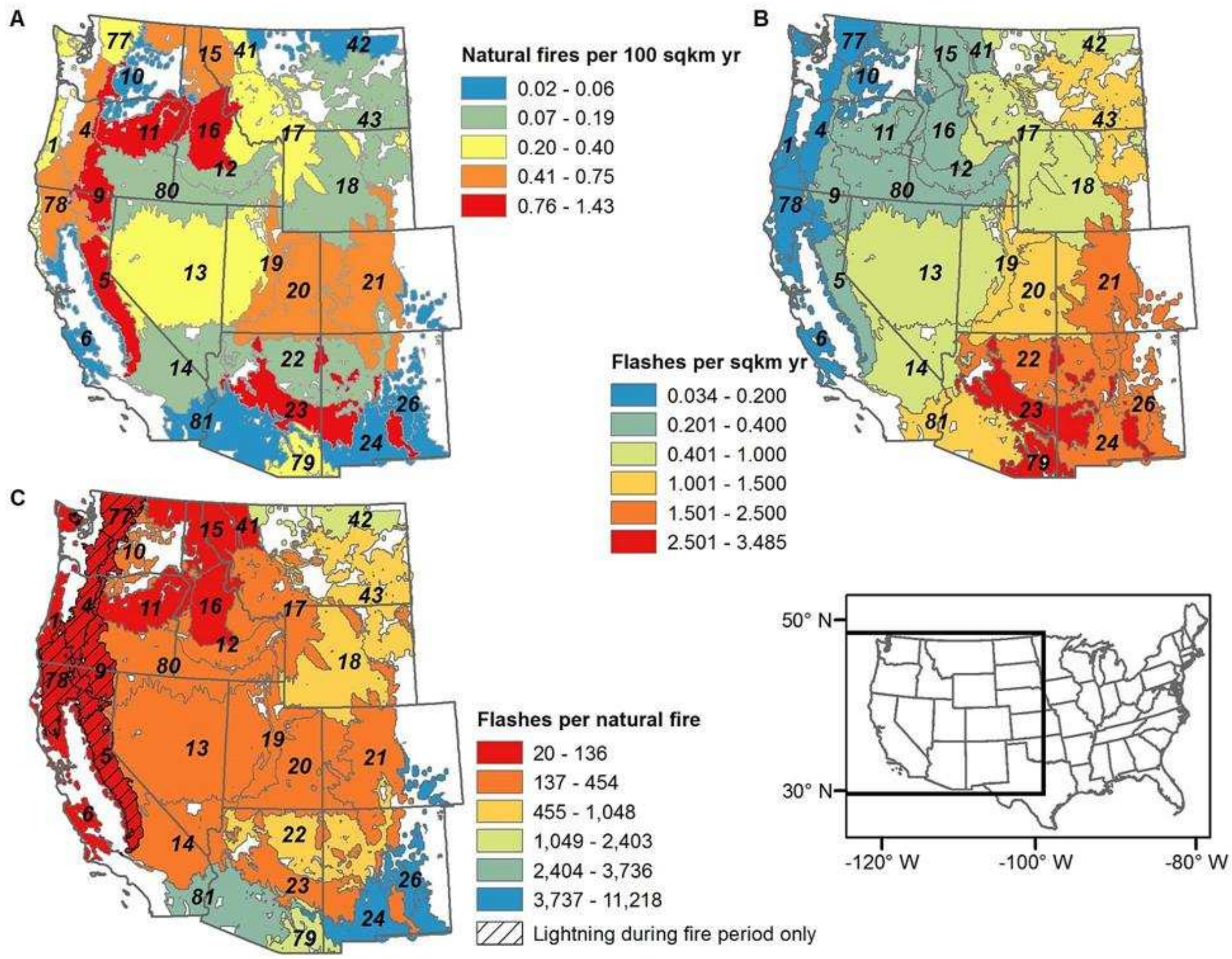

Figure 13: Broad-scale fire and flash density by ecoregion. (A) Fires per square kilometer per year from 2003-2007 by ecoregion, (B) Lightning flashes per square kilometer per year, and (C) Lightning flashes per fire. Hatching indicates the dominance of natural or anthropogenic causes by ecoregion (A) or the presence of lightning at locations only when fires also occurred. Numbers refer to table 3 Ecoregion ID listings.

pattern (fig. 14B). Flash density did not vary by proximity either before or after the fire or by period between before and after ($p>0.3$).

Lightning density and ecoregion relationships

Lightning density at fire locations varied by ecoregion (table 5). In low lightning areas like those mentioned above and the Central California Foothills and Coastal Mountains [6] and Columbia Plateau [10]; lightning was usually associated with fires. In the Arizona/New Mexico

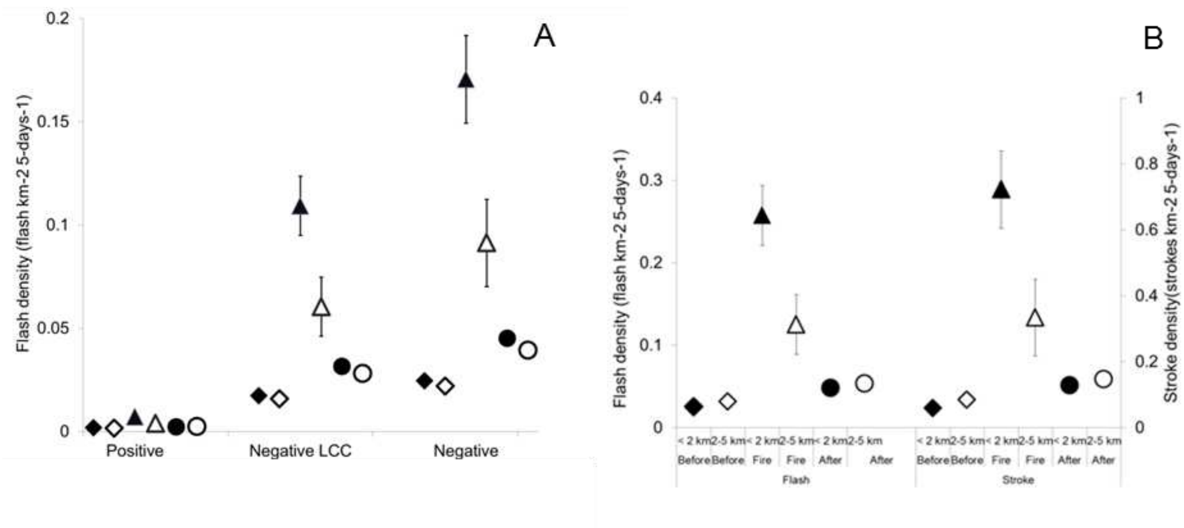

Figure 14: Flash and stroke density at lightning-caused fire locations across the western US during 2003-2007. (A) Flash density by flash type from source pool. (B) Flash density of all flashes observed at fire location. Symbols indicate time period and fire proximity: before fire (□), fire (□), after fire (□); closed symbols within 2 km of fire location; open symbols 2-5 km. Error bars show 95% confidence intervals. Within flash type, symbols without error bars are not significantly different (Tukey adjusted least squares mean difference p>0.05).

Mountains [23] and to a lesser degree the Arizona-New Mexico Plateau [22], lightning density was often as high during non-fire periods as during fire periods in other ecoregions. In these high lightning ecoregions, additional storms or increased storm intensity are unlikely to cause a significant wildfire increase and factors other than lightning density drive wildfire ignitions in these systems. In only two ecosystems, the Chihuahuan Desert [24] and the Northwest Glaciated Plains [42] were the levels of lightning not significantly different between the fire and off-fire periods. Both these ecoregions had comparatively low fire counts and large confidence intervals on the means.

Quantile relationships

Testing lower and upper quartile quantile relationships within ecoregions revealed that some regions had clear partitioning of lightning density during fire periods and off-fire periods while others did not (table 6, fig.15). Several ecoregions, most notably those along the west

Table 5: Mean (95% confidence interval) flash density at natural fire locations within ecoregions by temporal period.

ID	Number of locations	Pooled fire proximity during fire ($flashes/km^2$ 5-days)	Pooled off-fire periods and distances ($flashes/km^2$ 5-days)
1	34	0.126 (0.038,0.215)	0.004 (0,0.010)
4	660	0.118 (0.104,0.132)	0.006 (0.005,0.008)
5	1845	0.177 (0.168,0.186)	0.011 (0.009,0.013)
6	*12*	*0.091 (0.045,0.137)*	*0.000 (0,0)*
9	1154	0.155 (0.145,0.164)	0.007 (0.004,0.009)
10	*11*	*0.075 (0.017,0.134)*	*0.001 (0,0.004)*
11	2094	0.118 (0.112,0.123)	0.011 (0.010,0.013)
12	161	0.064 (0.054,0.074)	0.005 (0.003,0.007)
13	3550	0.171 (0.165,0.178)	0.039 (0.036,0.042)
14	855	0.272 (0.252,0.293)	0.069 (0.061,0.078)
15	1653	0.091 (0.086,0.096)	0.008 (0.007,0.009)
16	2178	0.081 (0.078,0.085)	0.012 (0.011,0.013)
17	1237	0.116 (0.108,0.123)	0.022 (0.020,0.025)
18	740	0.163 (0.152,0.174)	0.033 (0.029,0.038)
19	745	0.250 (0.232,0.268)	0.071 (0.064,0.077)
20	4572	0.230 (0.223,0.237)	0.067 (0.064,0.071)
21	2701	0.306 (0.294,0.318)	0.100 (0.095,0.105)
22	299	0.262 (0.226,0.297)	0.101 (0.081,0.122)
23	5397	0.452 (0.441,0.463)	0.165 (0.160,0.170)
24	**33**	**0.127 (0.062,0.192)**	**0.047 (0.024,0.070)**
26	22	0.227 (0.143,0.311)	0.066 (0.031,0.101)
41	233	0.066 (0.058,0.074)	0.007 (0.005,0.010)
42	**65**	**0.068 (0.040,0.096)**	**0.037 (0.018,0.055)**
43	1166	0.225 (0.206,0.243)	0.035 (0.031,0.039)
77	301	0.068 (0.060,0.076)	0.004 (0.002,0.005)
78	981	0.142 (0.133,0.152)	0.007 (0.006,0.009)
79	215	0.406 (0.355,0.456)	0.177 (0.147,0.207)
80	878	0.104 (0.096,0.111)	0.014 (0.012,0.016)
81	76	0.204 (0.150,0.258)	0.065 (0.039,0.091)

Notes: Bold entries are not significantly different between fire period and pooled off-fire periods. Italics indicates low lightning areas

coast (the Sierra Nevada [5], and the coastal mountains [4, 9, 77, and 78], italics in table 6) displayed clear thresholds - essentially there was no lightning except when fires occurred. Lightning storms, when present, always have sufficient lightning density for wildfire ignition. In contrast, many systems in the interior western US such as the Southern Rockies [21] and the

Table 6: Lower quartile (95% confidence interval) of pooled fire period flash density and upper quartile of off-fire period flash density by ecoregion.

ID	Ecoregion name	Fire period flash density (flashes/km^2 5-days)	Off-fire period flash density (flashes/km^2 5-days)
4	*Cascades*	*0.026 (0.026,0.026)*	*0.000 (0.000,0.000)*
5	*Sierra Nevada*	*0.051 (0.044,0.058)*	*0.000 (0.000,0.000)*
9	*Eastern Cascades Slopes and Foothills*	*0.051 (0.048,0.053)*	*0.000 (0.000,0.000)*
11	**Blue Mountains**	**0.038 (0.038,0.038)**	**0.006 (0.006,0.006)**
13	**Central Basin and Range**	**0.051 (0.048,0.053)**	**0.038 (0.033,0.043)**
14	Mojave Basin and Range	0.064 (0.051,0.077)	0.070 (0.055,0.085)
15	**Northern Rockies**	**0.026 (0.026,0.026)**	**0.006 (0.006,0.006)**
16	**Idaho Batholith**	**0.026 (0.026,0.026)**	**0.013 (0.011,0.014)**
17	Middle Rockies	0.026 (0.026,0.026)	0.032 (0.026,0.038)
18	Wyoming Basin	0.051 (0.043,0.059)	0.038 (0.031,0.046)
19	Wasatch and Uinta Mountains	0.076 (0.063,0.089)	0.089 (0.077,0.102)
20	Colorado Plateaus	0.064 (0.056,0.072)	0.083 (0.077,0.089)
21	Southern Rockies	0.089 (0.082,0.097)	0.134 (0.124,0.143)
22	Arizona/New Mexico Plateau	0.051 (0.031,0.071)	0.127 (0.105,0.150)
23	Arizona/New Mexico Mountains	0.153 (0.141,0.165)	0.242 (0.232,0.252)
41	**Canadian Rockies**	**0.026 (0.013,0.038)**	**0.006 (0.004,0.009)**
43	**Northwestern Great Plains**	**0.051 (0.045,0.057)**	**0.032 (0.026,0.038)**
77	*North Cascades*	*0.026 (0.026,0.026)*	*0.000 (0.000,0.000)*
78	*Klamath Mountains/California High North Coast Range*	*0.038 (0.030,0.047)*	*0.000 (0.000,0.000)*
79	Madrean Archipelago	0.140 (0.092,0.188)	0.255 (0.210,0.299)
80	**Northern Basin and Range**	**0.026 (0.020,0.031)**	**0.013 (0.010,0.016)**

Notes:
Bold entries are significantly different between fire and off-fire periods.
Italic entries are those in which the upper quartile of off-fire density is 0.
Ecoregions with no lightning during any period omitted.

Southwest [22, 23], showed no such distinction and the upper quartile of off-fire periods was larger than the lower quartile of the fire period. In these systems, lightning is not a unique or unusual event and other controls on wildfire ignition must be operational.

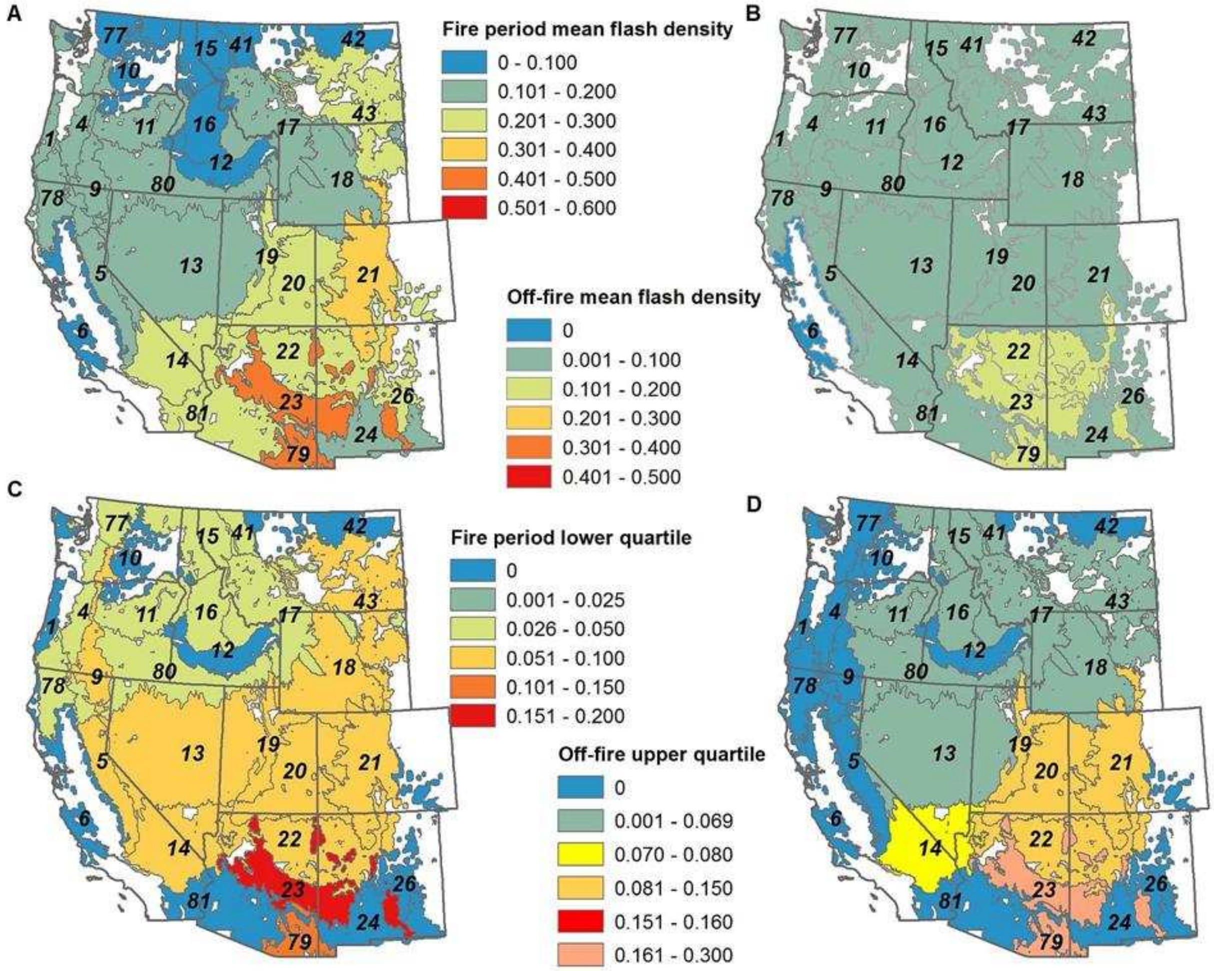

Figure 15: Mean and threshold flash densities (flashes/km2 5-days) at fire locations by ecoregion. (A) Pooled fire period mean density of fire locations, (B) Pooled off-fire period mean density for pooled distance and period, (C) lower quartile of pooled fire period density, and (D) upper quartile of pooled off-fire period density. Numbers refer to table 3 Ecoregion ID listings. See tables 5 and 6 for significance levels.

Discussion

These results demonstrate that lightning density, and in some ecoregions simple lightning presence, is a critical driver of wildfire ignitions in most western US ecoregions in contrast to properties such as polarity or multiplier. Average lightning density close to wildfires was significantly higher than during non-fire periods. Specifically, average lightning density was equivalent to 13 flashes km^2 yr at sites close to wildfires at the time of fire initiation, which is considerably higher than annual averages in the western US (0.1-6 flashes/km^2 yr, [Koshak et al. 2015]). Based on these results, in many ecoregions, wildfire ignitions are the result of storms that deliver elevated lightning flash rates with increased opportunities for ignition should these flashes impinge at flammable locations. In the western US interior, however, background lightning densities are consistently high suggesting other mechanisms limit wildfire ignition rates.

The importance of lightning frequency in shaping patterns of wildfire occurrence varies across the western US (figs. 13A and 13B) and ranges from areas where flash density is not related to patterns of fire to areas where flash density is closely related to fire pattern. The Southwest (e.g., the deserts and plateaus of New Mexico and Arizona) has a high volume of lightning but a low to moderate conversion of flashes into ignitions. The high ratio of flashes to ignitions in this semiarid region could be the result of limited fuels, the fact that many flashes are associated with intense rain events during the late-summer North American Monsoon, or a combination of the two. In contrast, in the maritime systems of the Pacific Northwest (e.g., the Coast Range or the Klamath Mountains), lightning, though rare, very often initiates fires. Overall wetter conditions in this region support more vegetation cover, which increases the likelihood that a lightning flash will strike flammable material. The Southwest could be considered ignition saturated in the sense that additional ignition sources will not necessarily result in increased fires. The caveat being that other conditions remain the same. Global warming (particularly in the southwestern US, [Cook et al. 2015, Stavros at el. 2014]) is expected to produce drier and warmer conditions, which will change fuel abundance and moisture with implications for lightning-wildfire relationships. The Pacific Northwest could be considered ignition-limited as more lightning would likely result in more wildfire ignitions.

These results also have relevance to understanding how changing patterns of anthropogenic fire ignitions might interact with climate change to shape fire occurrence in a warming world. Because humans can start fires even when atmospheric conditions are not conducive to lightning generation, anthropogenic ignitions can undoubtedly play a role in starting fires even in regions with significant amounts of lightning flashes such as the Southwest (e.g. the ~1,900 km^2 human-caused Rodeo-Chediski Fire in Arizona, 2002). Nevertheless, this analysis suggests that anthropogenic ignitions would be expected to have a much larger influence on wildfire occurrence in the ignition-limited west coast with decreasing influences moving inland and to the south. Because of the positive correlation between population and wildfires (Westerling and Bryant 2008, Syphard et al. 2007), population increases in the west, particularly in exurban areas with flammable fuels, could have significant implications for fire occurrence in the coming decades.

CHAPTER 4: IMPLICATIONS FOR FUTURE WILDFIRE PATTERNS

Introduction

The previous chapters demonstrated that it is unlikely that there are "special" wildfire igniting lightning flashes in the sense that an igniting flash has a suite of unique or rare characteristics. Lightning flashes with ignition potential (positive and negative with long continuing current) account for almost 70% of all flashes. If lightning is present, the odds of a potentially igniting flash also being present are high. For many ecoregions, there is a threshold for the lightning density required to result in wildfire ignitions. In others, lightning is frequently present without ignitions so that controls such as fuels and weather conditions determine ignition potential. In anticipating the impact the climate change may have on lightning frequency and in turn wildfire ignitions, consideration of these ecoregion differences is crucial.

The relationship between predicted climate change and lightning occurrence is uncertain. Under a doubled CO_2 scenario, models predict that the western US will see an increase in lightning from 6-50% (Krause et al. 2014, Romps et al. 2014, Del Genio et al. 2007, Price and Rind 1994b). It is unclear whether this increase will come as additional lightning events (e.g. more storms) or more severe lightning events (e.g. the same number of storms but each producing more lightning flashes) or a combination of both. Climate models (Trapp et al. 2007) suggest that across the US more days will be conducive to severe thunderstorms. In the western US, however, warmer and drier conditions are expected to reduce the number of convective storms overall although very strong storms will occur more often (Del Genio et al. 2007). Increases in atmospheric aerosols, because of drier climatic conditions and increased wildfires in the western US (Spracklen et al 2009), will increase nucleation sites with non-linear changes in lightning formation (Price 2013). In some regions, increases in aerosols may reduce the frequency of convection storms resulting in less lightning overall, however, in other regions the opposite may occur. With little current indication of the likelihood of any of these potential futures, this study followed Romps et al. (2014) and assumed a 12% increase in flash rate for every 1°C increase in global warming. Wildfire increase was estimated under two scenarios 1) assuming current storm frequency and a 12% increase in lightning density within these storms, and 2) assuming no change in storm intensity but instead a 12% increase in the number of storms. Future storm increases will likely be a combination of these.

Methods

Lightning density estimates from Chapter 3 were used and estimates for future lightning ignited wildfires were limited to ecosystems with at least 200 wildfires during 2003-2007.

Two scenarios were considered, recognizing that both are likely to occur in varying degrees. First, lightning events (storms) continue at their same frequency with a 12% increase in the lightning density (flashes/unit area) per storm. Second, storm intensity remains the same but there are 12% more storms. A 12% increase in flash density was evaluated for each ecosystem which exhibited a threshold of required minimum lightning intensity for ignition at the lower quartile (25%, see Chapter 3) by testing whether a 12% increase in the upper quartile (75%) of off-period lightning would equal or exceed the ignition density threshold. If the threshold was exceeded, the percent increase in wildfire ignition was determined as the percentile difference between the original density and the increased difference. To improve estimation, percentiles (1, 5, etc.) and deciles (10, 20, 30, etc.) of lightning density were estimated using SAS procedure QUANTREG (SAS 2002-2010) as was done for the quartiles in Chapter 3.

A 12% increase in storm frequency was evaluated by considering two possibilities. First, for ecosystems in which lightning was not present during non-fire periods (upper quartile of non-fire lightning equal to 0); any increase in storm frequency was assumed to increase wildfires at a 1-to-1 rate (since lightning was only found during fire periods). Second, for the remaining ecosystems, current percentiles of lightning density during non-fire periods were compared to the lower quartile of fire-period lightning (threshold) for each ecosystem. The decile/percentile of off-period lightning density (if any) which corresponded to the threshold level was taken as the current level of storms greater than the threshold, in that ecosystem. This percent was subtracted from 100 and multiplied by 12% to estimate the increase in fires due to increased storm frequency. Third, systems (such as the Arizona-New Mexico Mountains [23]) in which pooled lightning density was not significantly different from the threshold values at the upper quartile were evaluated. In this system, lightning frequently was often at threshold intensity even when fires did not occur suggesting that variation in lightning density was not a significant driver of wildfires and an increase in either storm frequency or intensity might not result in a significant increase in wildfires (in other words, these systems have plenty of current potential ignitions yet only a third of the time do they result in wildfires). In these systems since lightning was highly coupled with other drivers, no estimate of the impact of storm frequency was feasible.

Results

A 12% increase in lightning density was not sufficient to increase background lightning levels during off-fire periods to the fire-period threshold value in any of the ecoregions. A 12% increase in the number of lightning events, however, did result in increases in potential wildfire ignitions ranging from 1-12% per °C of global warming (fig. 16).

Discussion

Spatial variability in the importance of lightning density in the western US suggests that the consequences of increased lightning frequencies from climate change (Romps et al. 2104) will be location dependent. By the end of the century, global temperatures could increase by 3.6°C, in some ecoregions, and consequently wildfires due to increased lightning could increase by as much as 36% (Romps et al. 2014). Overall value computed here are somewhat lower than the estimates of Price and Rind (1994c:Table 2) for the western US (range 30-61% increase under a 2x CO_2 increase). Their highest increase was in the Southwest (Arizona and New Mexico) a area for which ignitions were not estimated here. Assuming that fuels remain the same, it is unlikely that increased lightning frequencies will significantly elevate wildfire occurrence in the interior western US. Predictions, however, are for earlier springs, longer fire weather seasons, and generally drier conditions throughout the west (Jolly et al. 2015, Williams et al. 2013, Westerling et al. 2011, 2006) so even in these areas, ignition potential will increase. In contrast, in systems where lightning is rare, increased lightning flashes associated with warming would be expected to act synergistically with drier fuels (Williams et al. 2013) and to elevate wildfire ignitions above what is expected based on climate alone. However, as more area is burned it is probable that fuel limitations (see for example Krause et al. 2014) will limit the ability of increased ignitions to increase wildfire occurrence.

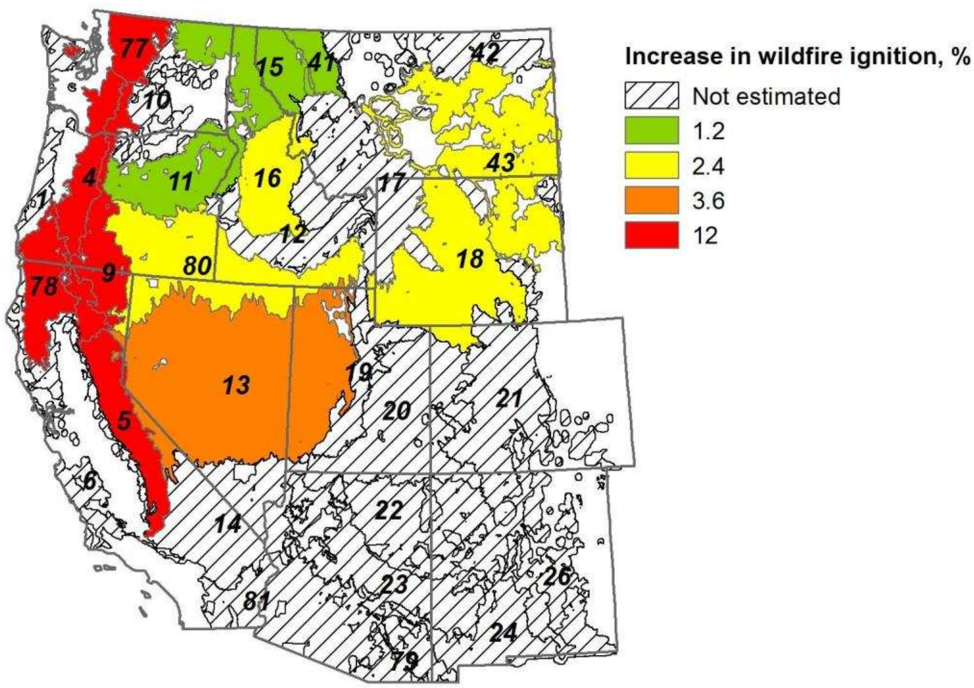

Figure 16: Percent increase in potential wildfire ignitions over 2003-2007 levels based on a 12% increase in lightning events for each 1°C increase in global temperature. Numbers refer to table 3 Ecoregion ID listings.

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