ANALYSIS OF SPATIOTEMPORAL VARIATIONS IN HUMAN- AND LIGHTNING-CAUSED WILDFIRES FROM THE WESTERN UNITED STATES (1992-2011)

by

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THESIS ABSTRACT

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The annual cycles of human- and lightning-caused fires create distinct patterns in time and space. Evaluating these patterns reveals intimate relationships between climate, culture, and ecoregions. I used unique graphical visualization techniques to examine a dataset of 516,691 records of human- and lightning-caused fire-start data from the western United States for the 20-year period 1992-2011. Human-caused fires were ignited throughout the year and near human populations, while lightning-caused fires were confined almost exclusively to the summer and were concentrated in less-populated areas. I utilize graphs and maps to demonstrate the benefit of a longer time frame in strengthening the findings and describing the underlying interactions among climate, society, and biogeography.

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I see you in every sunny day and every cheerful tune. Thank you for history, context, and poems, and teaching me to keep my chin up and my house clean.

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CHAPTER I

INTRODUCTION

Consistent yearly cycles underlie erratic annual features of fire-starts in the western United States. Unique methods of data visualization described by Bartlein *et al*. reveal the structure of these events, and also illustrate complex relationships between climate, human activity, and biogeography. Spatial and temporal patterns in lightning- and human-caused fire-starts are immediately apparent, but further exploration of causes and timing of fires uncover another facet: as over two-thirds of the wildfires each year are ignited by humans, and not only are climate and environmental factors vital to understanding these patterns, but the nature of the human activity that resulted in the conflagration becomes pertinent.

Humans were responsible for 326,453 fires during the twenty-year study period, while lightning accounted for only 190,238 fires. Human-ignited fires occur more regularly throughout the year with increasing frequency in notable areas and surrounding culturally significant events. Culture is further evident in regional habits and preferences as evidenced by peaks in fires on the first day of hunting season, or accidents related to patriotic displays of fireworks.

CHAPTER II

METHODS

I used the Fire Program Analysis Fire-occurrence Database (FPA FOD) painstakingly compiled by Short (2013). In an effort to create a comprehensive system of reporting that may unify the various wildfire reporting agencies, Short and her team combed through millions of records, ultimately presenting 1,594,673 records of wildfires in the United States for the period 1992 through 2011. These records were culled from federal, state, and local agencies, each of which, despite years of discussion about standardization, had its own individual style of reporting, with sporadic interagency collaboration. These agencies include the Bureau of Land Management (BLM), Bureau of Indian Affairs (BIA), National Park Service (NPS), United States Forest Service (USFS), the USFS Monitoring Trends in Burn Severity project (MTBS), the Oregon Department of Forestry, and the California Department of Forestry and Fire Protection, among many others. Each record contains a unique identifier for each fire, and the agency, discovery and containment dates, cause, the size of the fire in acres, latitude and longitude. Short describes in detail the process of selecting and cleaning the data in the FPA POD database; further processing of the dataset may find inconsistencies, but the effort likely would not significantly change the analysis.

From this large dataset I subset 516,691 records of fire-starts west of the 102nd meridian, which includes all or part of the following 15 Western states: Arizona, California, Colorado, Idaho, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oregon, South Dakota, Texas, Washington, Utah, and Wyoming. In the 20-year period, 1992-2011, 190,238 fires (about 37% of the total subset) were caused by lightning and 326,453 fires were started by humans. Short divided the causes of fire starts into 13 categories: 1) Lightning, 2) Equipment Use, 3) Smoking, 4) Campfire, 5) Debris Burning, 6) Railroad, 7) Arson, 8) Children, 9) Miscellaneous, 10) Fireworks, 11) Powerlines, 12) Structure, and 13) Missing/Undefined. For initial, broad analysis, I grouped these into 5 categories: "Non-lightning" includes everything that is not labeled "lightning." "All human" includes the twelve non-lightning categories except "missing/undefined," which could have been caused by lightning. "Deliberate" groups arson and debris burns, and "Accidental" describes fires most likely started accidentally – equipment use, smoking, campfire, railroad, children, miscellaneous, fireworks, powerlines, and structure fires. Finally, I plotted "All" of the fires together.

Analysis was performed using the statistical programming language R, with integrated development environment RStudio. These powerful tools allowed me to plot the hundreds of thousands of fire starts by category on graphs and separate maps against day and month of the year, to reveal the general spatial and temporal distribution of the fire starts. This informed the next step of drilling down into the individual classifications to determine which categories of fire are responsible for the patterns seen in the broader view.

With over 500,000 points of fire-starts of two types (human- or lightning-caused), decisions had to be made about presentation. Human- and lightning-caused fires were plotted in different colors in all but Figure 4. Figure Figure ***5*** and Figure Figure ***6*** involved the most overlap. Since human-caused were more widespread in their distribution plotted them first (in blue), with lightning-caused fires (red) on top. All points are slightly transparent, allowing high concentration areas to be bold and stand out against the areas with less fire intensity.

CHAPTER III

RESULTS

Overview

Human-caused fires occurred throughout the year, while lightning-caused fires were uncommon between October and May. All fires were greater in number during the summer. Humans started fires near population centers and recreation areas; lightning typically started fires in higher-elevation areas with lighter population density. All fires followed a general seasonal pattern, with more fires in the warm season and fewer fires in the cool season, but the numbers and locations varied greatly. These findings all point to a strong climatic effect, on lightning especially and the flammability of fuels, as well as the influence of human preferences, and available fuels. The graphs, maps, and diagrams below clearly outline these circumstances.

Intra- and interannual variations

Each year, fire-starts from all causes followed a seasonal trend, dipping to a low frequency in the winter, then spiking up in the summer (see Figure 1). Human-caused fires, on average, grew from a low at the beginning of each year, to a sudden peak at the 4th of July, then a gradual decline toward the end of the year. Memorial and Labor days often stood out, and New Year's Eve was the only anomaly in the annual winter slump in human-caused fires. Lightning-caused fires were rare mid-October to mid-May, with erratic spikes in frequency throughout the days in the middle of the year. Though no years are the same, the plot of the chaotic lightning record can be easily distinguished from the somewhat more predictable human-caused fire starts in the below graphs, even on a daily or weekly basis. Bumps near the end of each year, and around holidays, were usually driven by humans; spikes in the middle of the year – except 4th of July – could be confidently attributed to lightning.

While there were more total human-caused fires each year of this 20-year record, the most fires caused by lightning on any day of a given year was on average 164 more than the most fires on any day of that year caused by humans. When the peak daily frequency of human-caused fires in a particular year surpassed that of lightning, it was on average by only 67 fire-starts. The highest number of fires that lightning caused on any day of this record was 630, on 24 July 1994 – 258 more fires than the most caused by humans in that year. The highest number of fires that humans caused in this record was 434, on 4 July 2003. This happened to be one of the years when the daily maximum of human-caused fire-starts outnumbered those of lightning-caused – by a mere 41 fires.

In the eleven-year National Fire Occurrence Database record, Bartlein *et al.* (2008) found 1993 was the only year during which the peak daily occurrence of human-caused fires surpassed that of lightning-caused fires. This agreed with the FPA FOD dataset, and was the first year in which the peak daily frequency of human-caused fires exceeded that of lightning-caused fires. This was the case in only four other years of the twenty-year record: 1997, 2003, 2005 and 2007.

Figure 1. Total lightning- and human-caused fire-starts for each year, 1992-2011, plotted by day of the year.

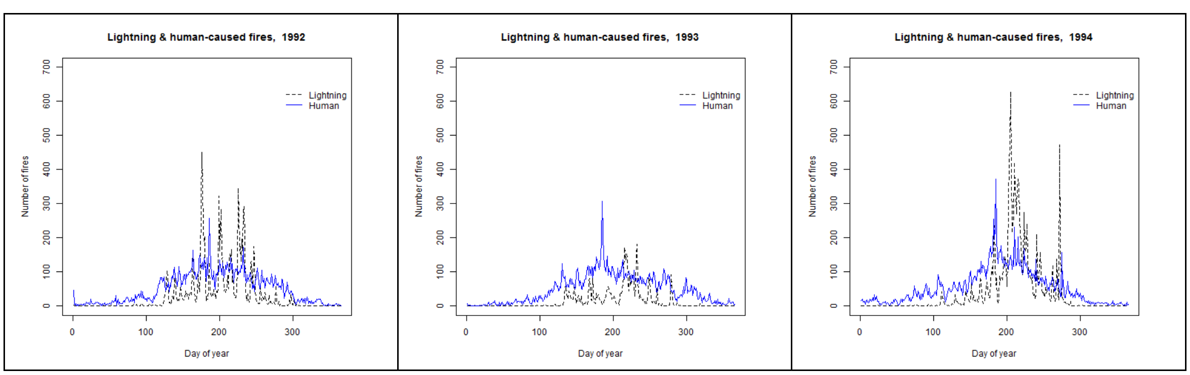


Figure 1. (continued).

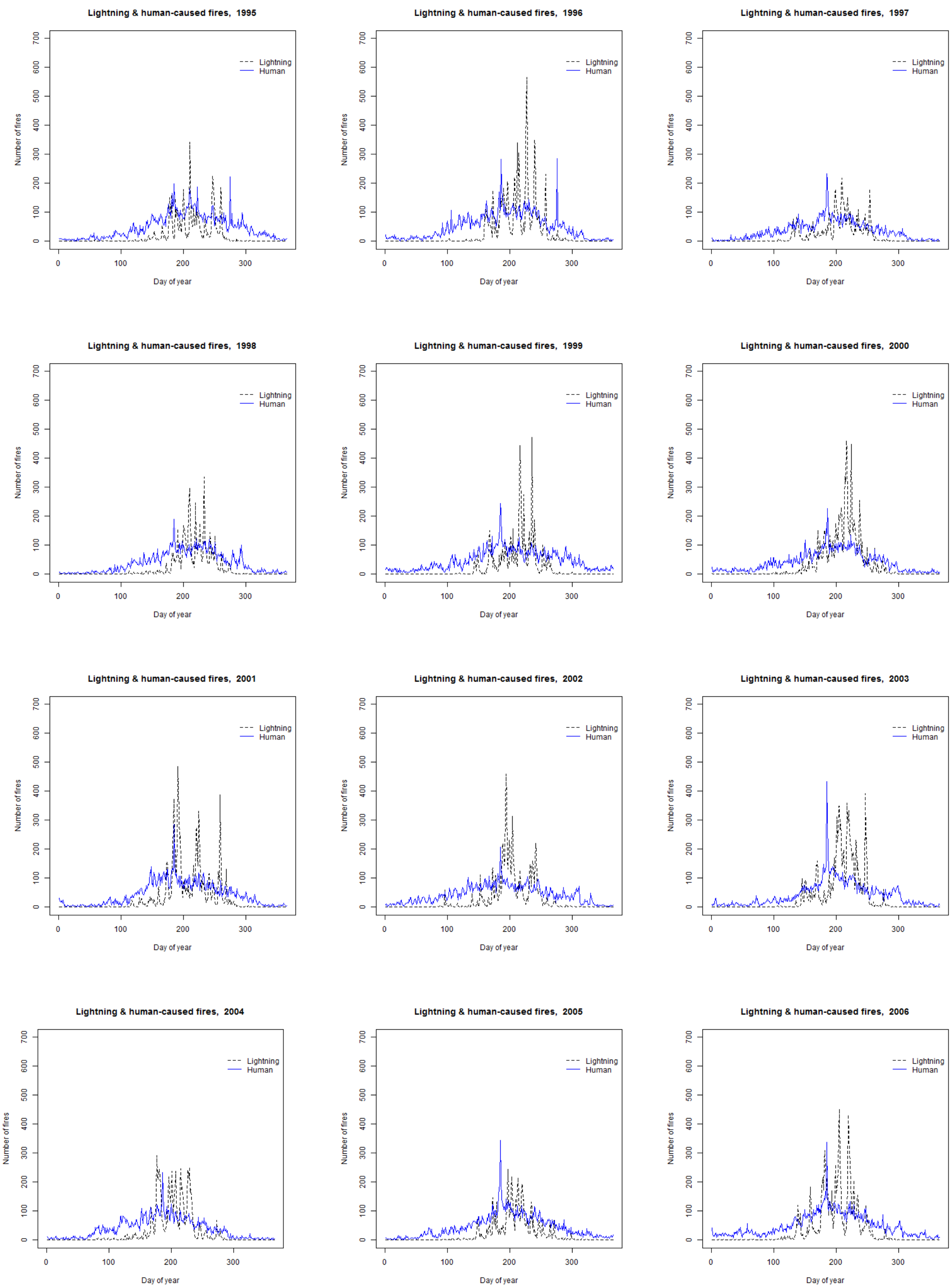
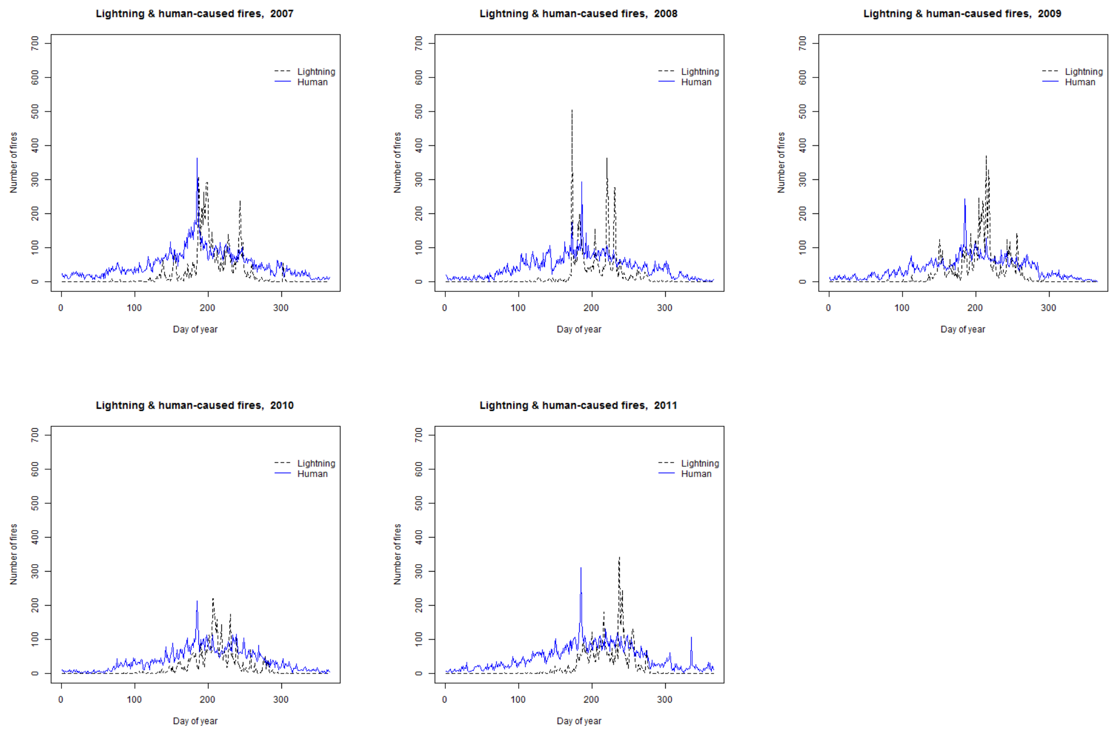


Figure 1. (continued)



Holidays

Dramatic dips or spikes in the plots of fire-starts throughout any given year were often seen in both human- and lightning-caused fires, pointing again to the influence of transient weather systems. Certain peaks and valleys in the plots, however, are completely cultural. Humans have created their own dispersed-throughout-the year fire season: federal holidays.

The "Independence Day singularity" (Bartlein *et al.* 2003, 2008) was prominent in this dataset (see Figures 2 and 3). In the five years (1993, 1997, 2003, 2005, and 2007) that the daily peak frequency of human-caused fires surpassed that of lightning-caused fires, that peak was on the 4th of July. In fact, Independence Day had the most human-caused fires in every year except 1995 and 1996. The increase in the number of human-caused fires on 1 October of these years is due in large part to a rash of fires across eastern Wyoming. 1 October 1994 also had an abnormally high number of human-caused fires. These fires were started mainly in and near national forests, and Casper – the second largest city in Wyoming. The majority of these fires were unfortunately listed as "Missing/Undefined" in the FPA FOD dataset.

Climate and culture join in the most disastrous way on Independence Day. It is not surprising that the combination of fireworks and warm, dry days lead to the most human-caused fires in all but two years of the twenty-year record. Lightning-caused fires were particularly low in 1993, 1997, 2005, and 2010, but patriotic celebration was not dampened by the weather in these years. The total number of fires skyrocketed in 2001, because lightning-caused fires happened to occur on Independence Day, boosting the otherwise average number of fire starts.

Other holidays that stood out are Memorial Day and Labor Day, and to a lesser extent New Year's Eve, the first few days of January, Columbus Day, and Veteran's Day. Memorial and Labor days are traditional times for Americans to go camping. The passing of a year and beginning of a new one are often celebrated with fireworks and sparklers. Fires may peak slightly around the three-day weekends of Columbus and Veteran's days as people sneak in one last camping weekend before winter.

The beginning of October also marks the beginning of hunting season in Wyoming, which may explain the sudden burst in fires around Casper and in national forests of eastern Wyoming. These anomalies particularly stand out because they occurred at a time of year that fire-starts were otherwise on the decline. Even in 1994-96, the days preceding and following 1 October had very few fires. Because the spike in fires

Figure 2. All fire-starts in the western US, 1992-2011, by month and year.

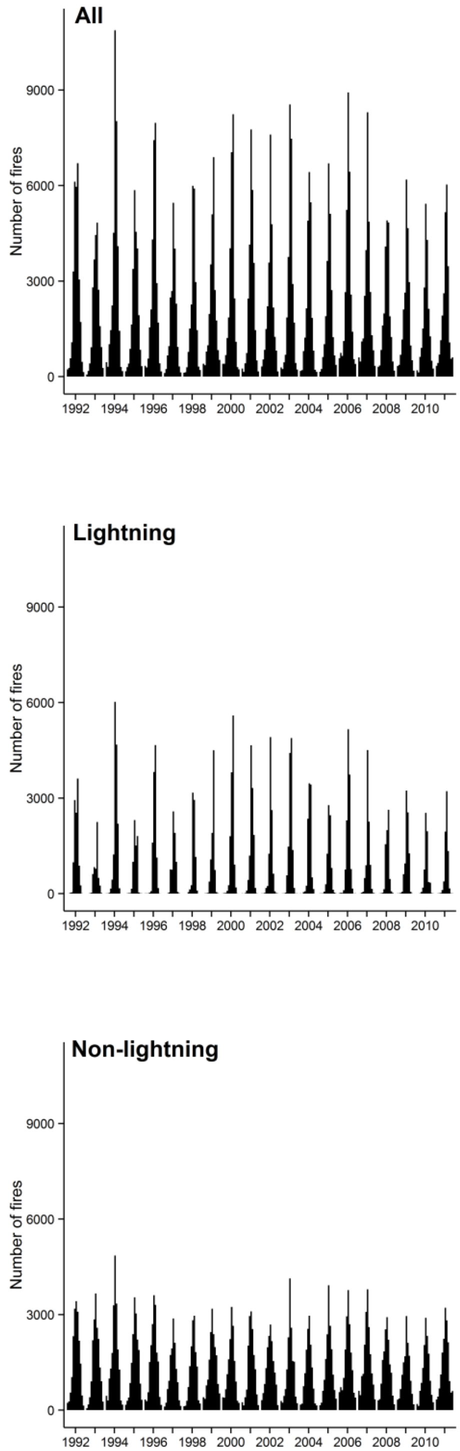
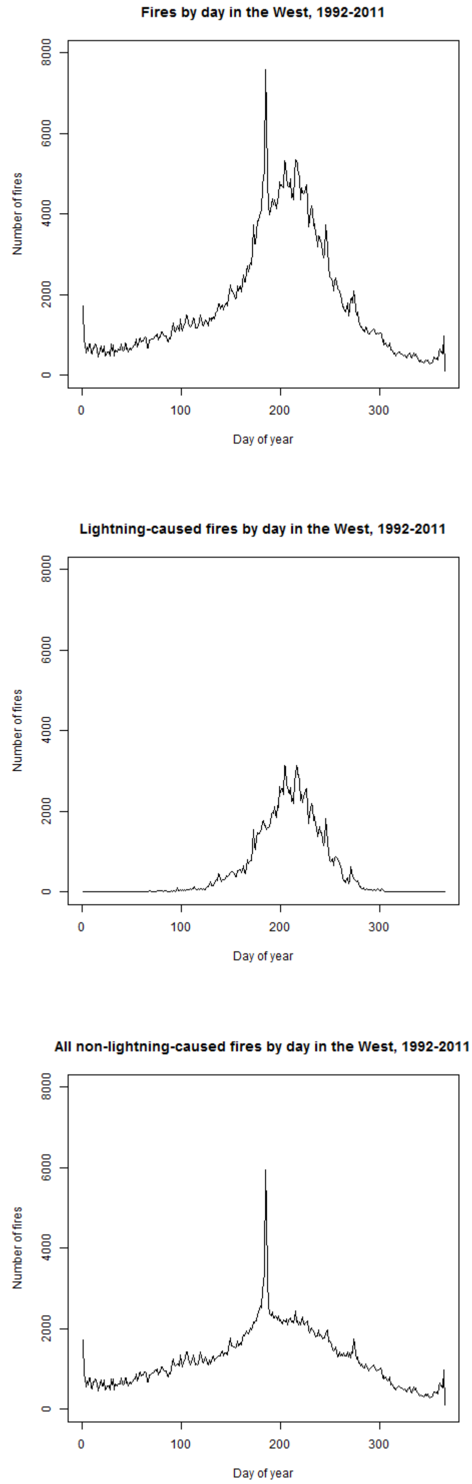


Figure 3. All fire-starts on all days of each year in the western US, 1992-2011, by day of year.



were on the same date each of these three years, and there was nothing unusual around this time of year in the lightning-caused fire record, this may be the date on which culture most strongly superseded the effect of climate.

Specific causes

Drilling down into the more specific causes revealed campfires, fireworks, and children as the driving forces behind the 4th of July fires. Fires listed as “children-caused” are more numerous on Independence Day than any other day of the year by far. The three-day weekends of Memorial and Labor Day also show peaks in child-caused fire starts.

Specific fireworks-caused fire starts were almost nonexistent until 1997, and were therefore likely underreported throughout the twenty years. Fireworks peaked on 4th of July, and random other days. New Year’s Eve 1999/2000 – the turn of the millennium – showed a small increase in fireworks-caused fires compared to surrounding days and the ends/beginnings of other years.

Fires stemming from campfires spiked at Memorial and Labor days; often the number of campfire-caused fires was very close or more on these holidays than Independence Day. Columbus Day and Easter also were perceptible amongst the campfire-caused fires.

Though the spikes in fires on the 4th of July did not appear to correlate to the particular day of the week 4th of July is observed in any year, it may be fruitful to see if falling on a weekend increases the number of fires for other holidays.

Fires caused by debris burns generally followed an opposite pattern to the aforementioned fire cycles. Debris burn fires tended to happen during weekdays, and dip at the holidays. This may point to the “debris burn” classification covering professionally administered fires, as opposed to those of private landowners.

Spatial patterns

Spatially representing the fire-starts gave a more robust view of the FPA FOD dataset, revisiting familiar patterns and uncovering others. Every ignition that occurred during the study period is plotted in Figure 4. Though the number of fire-starts varies quite a bit, the *patterns* of human- and lightning-caused fires hold across each year. Human-caused fires are focused around popular recreational areas, and those with relatively high human population density. Lightning-caused fires were concentrated in lower population, higher elevations areas. These patterns are explored in Figure 5 and Figure 6.

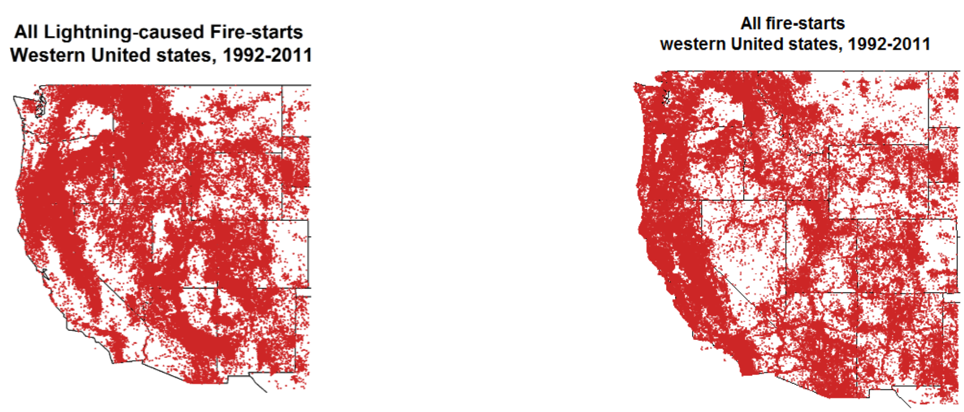


Figure 4. All lightning- and human-caused fire-starts for the study period (1992-2011)

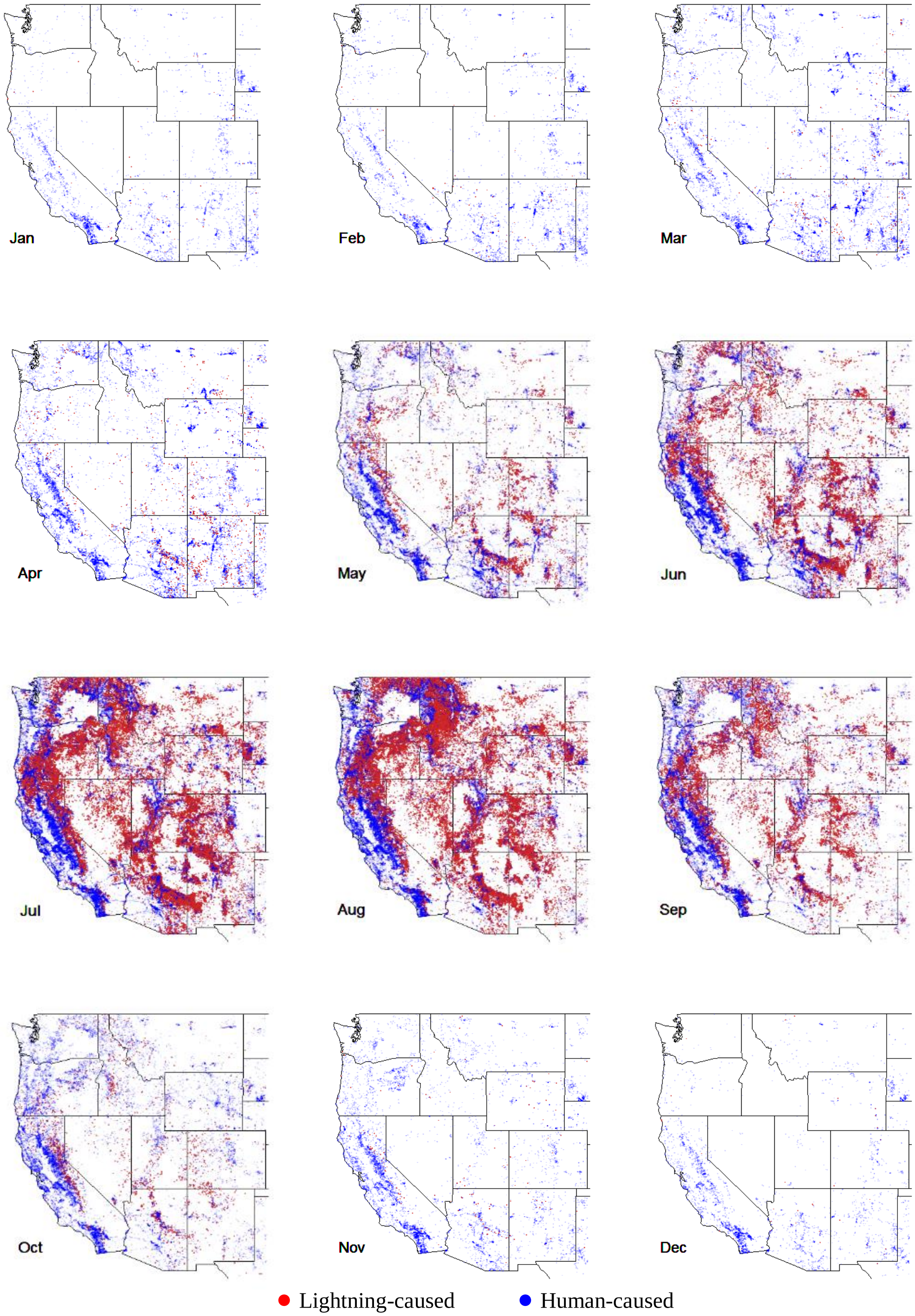


Figure 5. Each point represents one fire sparked during that month in any of the twenty years (1992-2011) of the study. Darker areas represent more fire-starts.

In May, the number of human-caused fires was on a steady increase in urban and recreational sections of the West, and lightning-caused fires were gathered along the eastern Rockies in Colorado, and along the southeastern edges of the Colorado Plateau. The map of June fires shows lightning- and human-caused fires starting to highlight the topography of the West; the peaks of mountain ranges stand out in red, shaded below by human-caused fires. High population and recreational areas and highways become a dark blue. At this point most years, fires became highly concentrated around the perimeter of the Colorado Plateau, with the Carrizo, Lukachukai, and Chuska mountains, straddling the Arizona-New Mexico border, forming an inverted question mark in the middle. These high-elevation areas, as well as the Rocky Mountains, San Juan Range and Mogollon Rim bordering the Colorado Plateau are clearly attractive to lightning, while the lower-elevation rivers and scenic canyons appeal to vacationers. In July, lightning-caused fires typically engulfed the eastern sides of the Sierra Nevada and Cascade ranges, the Blue Mountains of northeastern Oregon, and up into the Rocky Mountains of Idaho, creating a ring around the Columbia Plateau.

Human-caused fires then spread north and inland across the country, supported by the dry conditions and increased onshore flow provided by the poleward retreat of the jet stream and amplification of the southwestern monsoon (Bartlein *et al.* 2008). The blue symbolization on the map gives a false impression of human-caused fires as a river sloshing from Oregon, across Idaho, into Utah, then spreading across Arizona. August monsoons often brought relief to the outskirts of the Colorado Plateau, as well as southeastern Arizona and southern California (Westerling *et al*. 2003; Bartlein *et al*.

2008). The Basin and Range fire areas became more patchy, while most of California and the outskirts of the Columbia Plateau, especially the Idaho Rockies, were still in the thick of fire season.

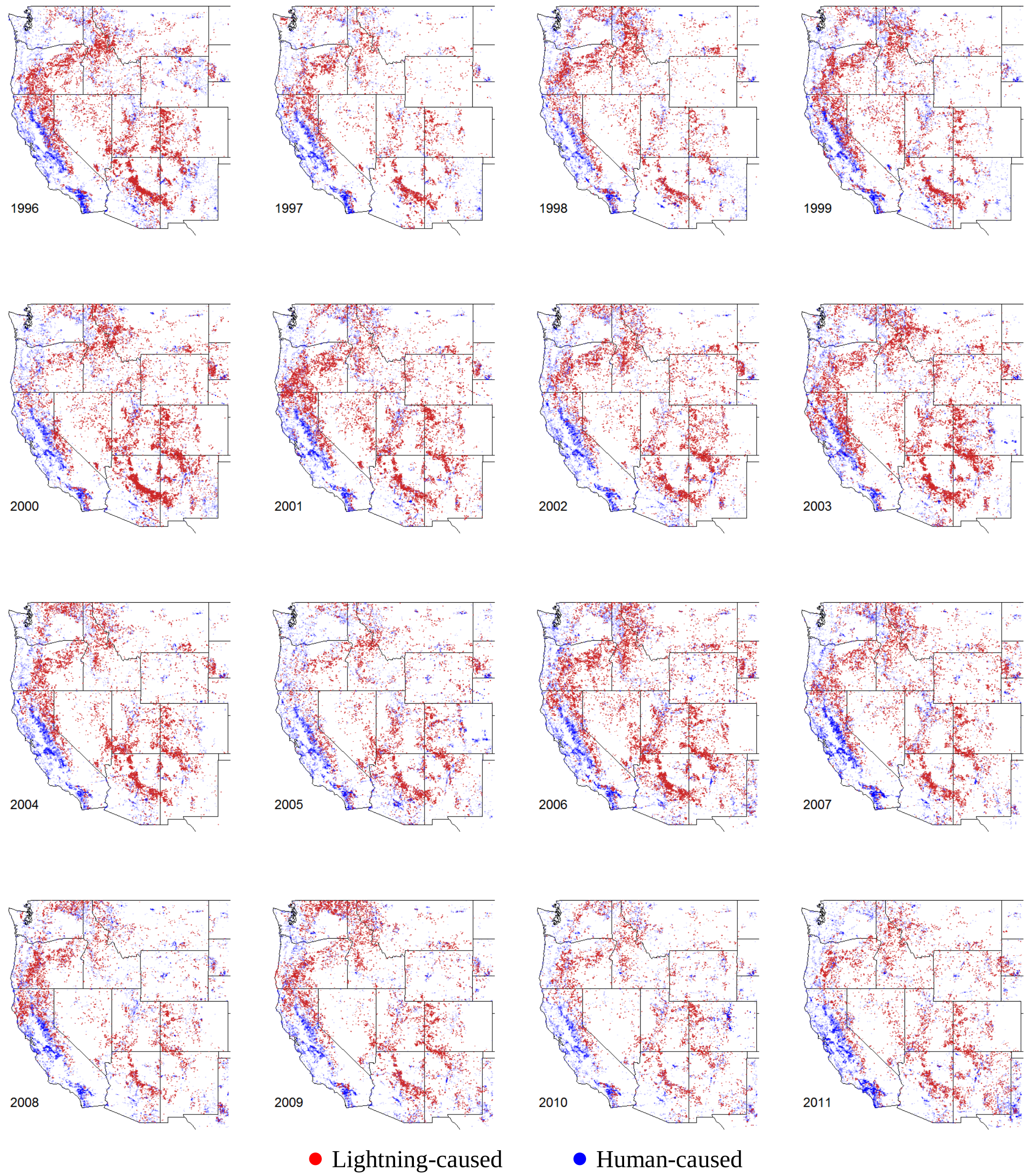


Figure 6. The total number of fire-starts that occurred in each year of the dataset. Each point represents one fire sparked during that year. Darker areas represent more fire-starts. Notice the seasonal progression across the map.

By October, the lightning-caused fires had practically disappeared, but humans were still igniting the areas of the west that are, in many years, still suffering from drought (Bartlein *et al.* 2008). These regions include the western Sierras, Southern California, along the plateaus, and a variety of other recreation areas and outskirts of towns. The mountains of the western states are still visible in November, as are the Blue Mountains, and Mogollon Rim, but the Black Hills National Forest and Pine Ridge Indian Reservation in South Dakota stand out for the first time. By December, Southern California, northern stretches of the western Sierras, southwestern South Dakota and faint patches of Arizona and New Mexico comprise most of the areas still suffering from human-caused fires. The reprieve is short, as fires already start increasing again in January, have spatterings across the Southeast in February, and start filling in the valleys again by March.

CHAPTER IV

DISCUSSION

Overview

Although the plots of human- and lightning-caused fire-starts are distinct, (Figure 1) they accentuate the commonalities between the two phenomena. Plotting these phenomena across the geography of the West revealed the more discordant, complex side of this dataset.

High population density, as mentioned before, had a strong relationship to the number of nearby human-caused fires. Humans not only started fires where we live and play, but also an ample amount of fires along the routes that take us between the two. Especially in the summer months, the fires tracing popular highways are unmistakable. The "waterfall" from Oregon to Arizona very closely follows the path of interstates. Northeast Oregon, across southern Idaho and into Salt Lake City, Utah, is Interstate 84. From there, Interstate 15 cuts across Utah, the northwestern tip of Arizona, and into Nevada. Also very clear are the desert interstates leading between southern California and Las Vegas, Nevada and cities of central Arizona. Humans also started fires along the western edge of the Sierra Nevadas, and along Interstate 5 from California through Washington.

Lightning-caused fires created patterns that were almost completely the opposite to those of human-caused fire-starts. Though lightning is most likely to start fires in areas with relatively low population density, such as forests and higher elevations along the mountains, there are blank areas on the maps where fires are seldom started by either humans or lightning. Areas uninhabitable by humans are often deemed as such because they are also uninhabitable by other species, and therefore likely to lack fuel for fires of any type (Parisien *et al.* 2012) . Roads are visible, in some of the maps, but in negative space, and always along mountain passes or other canyons, except in southern California. Lightning-caused fires were far more common at high elevations; adding an axis for altitude in these maps might be useful for analysis, but the record does not contain altitudinal data.

The interannual variation of fire-starts in this record stand out starkly in the yearly maps (Figure 5 and Figure 6), but the overarching story is the same. The number of fires, and exact locations varied, but the Colorado and Columbia plateaus still stand out against the ponderosa and Doulas fir forests growing around them. Southern California is perpetually on fire, and human- and lightning-caused fires take up opposite sides of the Sierra Nevada and Cascade mountain ranges (west and east, respectively). The roads across deserts and major interstates are highlighted by human-caused fires, and stretches of canyon, often sandwiching highways, are negative-space lines through the patches of lightning-caused fire locations (particularly in 1997, 1999, and 2006).

<u>Climate</u>

Littell *et al.* (2009) found that up to 64% of wildfire area burned is directly attributable to climate, and when Parisien *et al.* (2012) removed “percentage fuel” from their models – which had been the strongest predictor of wildfire likelihood – it only slightly altered their predictions, suggesting the percentage of available fuel was acting as a proxy for other variables, such as climate and human settlement. Ireland *et al.* (2012) found that, while climate is definitely a very strong control on wildfire on a broad scale, at finer scales, vegetation seems to be more important.

Winter precipitation a year previous to fire season is a strong predictor of area burned by wildfire in arid areas. Similarly, the Sierras, southern Rockies, and Great Plains best correlated with precipitation for all seasons along with significant year-of-fire relationships, suggesting build-up of fuel in these areas can lead to larger fires. Precipitation in spring and summer in the California woodland, chaparral, and dry steppe dampens the likelihood of extensive fires in the following season (Littell *et al.* 2009). El Niño can affect the timing of snowmelt in the Pacific Northwest (Hessl *et al.* 2004), and rainfall effects after an El Niño event last up to eight months in chaparral and evergreen forests (Garcia 2010) , which may explain California's mild 1998 wildfire season, following a very strong El Niño, as well as the moderate fire season in the Pacific Northwest in accordance with the subsequent La Niña.

There are multiple ways that precipitation and high temperatures effect the amount and extent of wildfire. Fuels, whether growing in a wet winter or drying out in a hot spring, depending on the controlling factor in the area, directly affect the possibility of wildfire. Weather provides the moist or stifling conditions, and possibly lighting to ignite them. By controlling humans, climate indirectly has an effect on the fire season: people are far less likely to partake in outdoor recreation if it is too cold or wet outside (Wall *et al.* 1986) , which means fewer people lighting fires that may get out of control.

The Mogollon Rim, where the Colorado Plateau drops into central Arizona, illustrates well the convergence of climate, topography, biogeography, and human behavior. This area is vulnerable to lightning because of its high elevation – up to 600 meters above Verde Valley – and location in the pathway of storms (Barbaris and Betterton 1996). This mountainous tropical/subtropical desert (Bailey 1996) receives forty to fifty-percent of its precipitation in winter, when storms pass over the state on southwesterly winds. These storms help maintain ponderosa pine forests along the Rim's drainage area (Barbaris and Betterton 1996), which may encourage return fires with its productive understory and needle litter (Ireland *et al.* 2012). Finally, human-caused fires are a product of the plethora of recreational options along the Rim, such as camping, fishing, star-gazing, cycling, kayaking and many others. The combination of storms, fuel, and fun kept the number of fires in this area high.

CHAPTER V

CONCLUSION

An examination of maps of wildfires in the western United States reveals consistent yearly cycles underlying variable features of each year. Visualizations of the data describe the structure of these events, and also illustrate complex relationships between climate, human culture, and biogeography. Climate is a strong influence in lightning-caused fire, but, since humans are adept at starting fire, population density is also a very strong influence on the number and extent of fires annually. For every question answered with each visualization method, the project was enriched with further challenges. This dynamic view of the spatial and temporal landscape provides an excellent base from which to explore the many variables of the wildfire structure in the western US. The FPA FOD dataset provided over fifty-percent more records than the NFOD utilized by Bartlein *et al.* (2008), with six (1992-1996) overlapping years. Findings regarding the timing and location of fires in the western US were very similar across the two datasets. The standardization of reporting procedures to the FPA FOD, if it is maintained, will lead to even more and better insights about wildfire. The inclusion of many human-caused subcategories allows for analysis of human behavior on a finer scale than previously possible. Further interrogation of the spatial and temporal features of wildfires may eventually inform wildfire protection techniques, as vacationer and resident choices.

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