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Exploratory Analysis of Environmental and Social Drivers of Wildfires: Oregon, USA

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Bachelor of Science
McGill University
2013

Thesis Committee Chair: Yang Liu, PhD

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An abstract of
a thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University
in partial fulfillment of the requirements for the
degree of
Master of Public Health
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Abstract

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Wildfires are an ecological disturbance intrinsic to many forest, shrub land and grassland ecosystems and play an important role in shaping these ecosystem processes. Despite the necessary (and often) beneficial role of wildfires, they have numerous harmful impacts. From a public health perspective, wildfires adversely affect human mental and physical health. There is rising concern that these undesired health outcomes will intensify in the future as climate models predict an increase in wildfire frequency, severity, and extent throughout the United States. This study sought to explore historic wildfires and understand what anthropogenic and environmental factors are key drivers for wildfire incidence in the state of Oregon. We employed basic descriptive statistics, ANOVA, and univariate logistic regression to achieve this end. Results from the analyses showed that wildfires are increasing in both frequency and extent throughout the state. Furthermore, environmental variables including drought, temperature (average, maximum, and minimum), precipitation, and land cover type are significant predictors for wildfire occurrence in Oregon. This study was the first to assess the importance of such variables for wildfire incidence in Oregon.

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Table of Contents

List of Tables and Figures

Introduction

Wildfires are an ecological disturbance intrinsic to many forest, shrub land and grassland ecosystems and play an important role in shaping these ecosystem processes [1, 2]. Despite the necessary, and often, beneficial role of wildfires, they have numerous harmful side effects. From a public health perspective, a large amount of research has shown wildfires adversely affect human mental and physical health [3-5]. There is rising concern that these undesired health outcomes will intensify in the future as climate models predict conditions that will increase wildfire frequency, severity, and extent throughout the United States [1, 2, 6]. Recent studies have attempted to synthesize trends in wildfire incidence across regions focusing on one or all of the primary elements necessary for wildfire initiation and spread – fuel source (vegetation type and amount), environmental conditions that favor ignition (temperature, drought, precipitation levels), and ignition source (natural, anthropogenic) [7-12]. However, all of these factors have large variability based on local conditions and management practices. Accordingly, classification of environmental and anthropogenic drivers of wildfires requires a more regional perspective. This study seeks to understand what anthropogenic and environmental factors are key drivers for wildfire incidence in the state of Oregon. The results of this study will help local public health departments and land managers prepare for wildfire risk and vulnerability.

Wildfires

For the purpose of this study, wildfires are defined as unplanned, unwanted wildland fires in shrub land, forests, and grasslands where the objective is to extinguish the fire [13]. Wildfire occurrence, extent, and impact are defined by the availability of ignition sources, amount of fuel to burn, and environmental conditions favoring combustion – or more simplistically heat, fuel, and oxygen [8, 12]. Together heat, fuel, and oxygen compromise the fire triangle. In order for a wildfire to ignite and propagate all three of these factors must be present. Fire ignition occurs when fuel and oxygen are exposed to heat and join in a chemical reaction. The fire propagates as more fuel is ignited via convection, conduction, or radiation. Convection, the process by which movement of hot air or fluid heats a fuel source, is the most common mode of spread for wildfires [14]. A fire will continue to burn until one or all sides of the fire triangle are removed or exhausted. While wildfires adhere to the general fire triangle, the primary components (heat, oxygen, and fuel) are strongly regulated by environmental and social factors and so are subject regional variability.

Environmental Variables - Climate

As wildfires are a physical process highly regulated and dependent on their physical environment, they can only occur when the environmental conditions are suitable for wildfire initiation and propagation. Consequently, previous studies have focused on analyzing trends in environmental conditions, such as temperature, precipitation, and drought and their impact on wildfire distribution and ignition [7, 15-17]. Regardless of the temporal or spatial scale of these studies, they conclude that warmer, drier conditions with decreased precipitation result in increased wildfire frequency. This is largely due to the impact of warm and dry temperatures on fuel source suitability. Fuel source suitability to propagate fires is heavily influenced by chemical composition and moisture content. Fuel chemical composition is primarily determined by fuel type (species) [18], where as moisture content is influenced by fuel type (e.g. species, size, dead/alive) and multiple climatic conditions preceding the fire event (e.g. precipitation, drought, temperature extremes) [1, 12]. Fuel moisture content is the amount of water a fuel contains and is the most important factor in determining fuel source flammability [14, 19]. Temperature, humidity, and precipitation levels of the surrounding environment regulate the moisture content of fuel sources. Specifically, warmer, drier, conditions with low precipitation indicate low moisture content. Fuel sources with low moisture content ignite more rapidly than moisture rich sources, since fire must exhaust the moisture before the fuel can ignite. While climate and fuel suitability are prime indicators of wildfire ignition and extent, regional topography plays a chief role in wildfire spread and distribution.

Environmental Variables - Topography

Topographic conditions, such as, aspect, slope, and elevation, have a strong affect on wildfire distribution and behavior [14]. This influence is due to topography's impact on moisture content, climate, and vegetation (fuel). Slope aspect directly influences the amount of sunlight a region receives and so the amount of vegetation and moisture present. Southern and western facing slopes receive and increased degree of sunshine. This results in a warmer drier climate with a greater number of fires than their northern counterparts [14]. In contrast, northern facing slopes tend to be cooler and support a greater degree of vegetation that maintains moisture longer, decreasing habitat suitability for wildfires. Slope itself regulates wildfire behavior through the speed of propagation. Warm air rises, meaning that fuels up hill of a wildfire are preheated. This translates into wildfires traveling faster uphill than downhill [14]. Additionally, a higher slope at the head of a fire brings flames into closer contact with additional fuel sources encouraging spread. In addition to aspect and slope, elevation indirectly regulates wildfires via its affect on climate. Decreased precipitation and increased temperatures at low elevations favor combustion and wildfire, where as wetter cooler temperatures prevail at higher elevations decreasing wildfire risk [14, 20].

Social Variables

Supplementing environmental variables, social variables play an important role in wildfire ignition and fuel source availability. Wildfire ignition can be anthropogenic or natural in origin. Summary statistics from the United States Department of Agriculture [21] from January 2000 to December 2008 show that natural/lightning induced wildfires account for 45% of all wildfires and 80% of the area burned on federal land (Table 1). Conversely, when comparing the Eastern and Western United States these statistics shift. In the Western United States natural causes account for 65% of federal wildfires, where as in the Eastern United States, natural causes make up only 11% of all wildfires and arson accounts for 40% (Table 2). Several studies articulate that differences in the importance of anthropogenic vs. naturally caused fires can be can be explained by regional variation in environmental (climate and topography) and or social factors (population density, road density) [22-25]. For example, studies have shown that increases in population and road density correlate with higher frequencies of human ignited wildfires [22, 26, 27]. Additionally, other studies have hypothesized that anthropogenic alterations to land cover have led to shifts in regional fire regimes via disturbances to the type and amount of fuel sources available [21, 28].

Wildfires in Oregon

Recent decades have witnessed an increase in wildfire number and extent across the western United States [2, 10]. Oregon in particular has seen a 1.95 acre per square mile increase in land burned from 1999 – 2013 compared to 1984 -1998 [2] and the Oregon Department of Forestry reported the last three wildfire seasons were among the most expensive and severe on record. With drought plaguing roughly 86% of the state, it is expected fire seasons will continue to be longer and more severe.

Oregon's climate is generally described as diverse and is heavily influenced by the Pacific Ocean bordering the state to the west and two interior mountain ranges parallel to the coastline, the Coast Range and the Cascade Mountains [29]. The Coast Range lies closest to the Pacific reaching elevations of 4,000 feet. These peaks force moisture rich air from the Pacific to move upwards as it moves east. As a result of the cooling and condensing of this air, the high western slopes of the Coastal Range experience some of the heaviest rainfall in the United States [29]. Roughly 75 miles inland lays the Cascade Mountains. These mountains act as the main divider between the eastern and western sides of the states. The Cascades reach a maximum elevation of nearly 11,000 feet. Similar to the Coast Range the Cascades encourage precipitation via the cooling and condensing of air moving across its peaks. As much of the moisture in the air has been reduced through its passage over the Coastal Range, the western slopes of the Cascades receive only between one half and two thirds the amount of precipitation as the Coastal Range [29]. Precipitation levels quickly decline east of the crests of the Cascade Mountains. Given that a majority of the moisture has been depleted from the air by the time it reaches east of the Cascades, eastern Oregon's climate is less moderated by the Pacific Ocean [29]. The climate in central and eastern Oregon tends to be warmer and drier year round than western Oregon, with temperatures exceeding 100° F. The strong variations in climate and precipitation between eastern and western Oregon have a strong influence on vegetation type and abundance. Wetter milder temperatures in the west favor Mesic forests, where as the warmer drier climate of the east favors drier forest types (specifically the ponderosa and juniper) [30]. Differences in vegetation and their interaction with climatic variables determine habitat suitability for wildfires. Increasingly warmer drier summer temperatures in western Oregon deplete fuel moisture in Mesic forests increasing wildfire risk [30]. In contrast, conditions favoring vegetation growth during the winter season determines habitat suitability for wildfires in eastern Oregon [30]. Despite seasonal differences in climate conditions influencing wildfire risk, projected climate models indicate wildfire activity is expected to increase across all vegetation types in Oregon and the western United States [1, 31, 32].

While variations in topography, vegetation, and climate throughout Oregon influence wildfire distribution, a source of ignition is also required. As previously mentioned close to 65% of fires in the western United States are ignited by natural causes, specifically lightning. As some evidence points towards increases in lightning activating in the western United States accompanying climate change, there is potential for an increase in ignitions [33]. Additionally, the population of Oregon has grown 5.2% in the last 5 years [34], bringing with it-increased concern for rate of human caused wildfires. As previous studies have found that high population densities increase the likelihood of human induced wildfires [22, 27, 35]. With wildfire rates increasing throughout Oregon, it is important to utilize proper geospatial and statistical approaches to understand the factors important for driving wildfires to help protect human and environmental health.

Wildfires and Health

Future climate models predict an increase in temperatures and longer drier seasons resulting increased wildfire, frequency, severity, and extent throughout the United States [1, 2, 6]. As a result, exposure to air pollution from wildfire emissions is also expected to increase. This has serious implications for environmental and anthropogenic health risks associated with wildfire emissions in the coming years [5]. Wildfire emissions are highly variable and composed of several hundred different chemical compounds including water vapor, carbon dioxide, carbon monoxide, benzene, and particulate matter (ranging from less than 2.5 to 10 micrometers) [36]. The combination of these compounds is determined by the wildfire fuel source, temperature, and wind [36]. Recent comparisons of global fire emissions and carbon emissions estimate that CO_2 emissions from wildfires account for nearly one third of all carbon emissions globally [37]. This contribution can have profound impacts on atmospheric carbon levels and global warming rates especially during the regrowth phase, when carbon reuptake is significantly reduced in the area.

In addition to the environmental impact of wildfire emissions, the small particles (PM2.5 and PM10) associated with wildfire smoke have significant adverse health outcomes for exposed populations [36]. The EPA and WHO each provide 24 hour mean air quality standards for PM2.5 (EPA 35μg/m3, WHO 25 μg/m3) and PM10 (EPA 150 μg/m3, WHO 50 μg/m3) respectively, and studies in Canada and Spain have found ambient air levels of PM2.5 during wildfires between 6 and 75 times higher than the

WHO accepted level [36, 38]. Exposed populations can be thousands of miles away from the fire perimeter and the exposure period ranges from a few days to several weeks. Broadly, exposure to the particulate matter associated with wildfire smoke has been strongly linked to respiratory morbidity and all cause mortality [3, 5, 36, 39]. Other researchers have found associations with cardiovascular morbidity and mortality, but several reviews conclude that the link has not been adequately researched to inform general conclusions [5, 36]. While strong associations between wildfire smoke and respiratory morbidity have been found, not all populations are so adversely affected by wildfire smoke. Health impacts are highly dependent on the amount and duration of exposure coupled with age, health status, pre-existing conditions (specifically asthma and COPD) and other socioeconomic factors [5, 36, 40, 41]. Beyond physical health outcomes associated with air pollution, wildfires can pose a risk to community mental health. Recent studies suggest populations exposed to wildfires are at increased risk for adverse psychological outcomes such as posttraumatic stress disorder and major depression [42, 43]. As the climate changes and housing development expands along the wildland-urban interfaces, more communities are increasingly vulnerable to the adverse health outcomes associated with wildfires [44] (Figure 1).

Purpose of Study

This overall study seeks to understand what anthropogenic and environmental factors are key drivers for wildfire incidence in the state of Oregon. As well as develop a causal pathway exploring the important inputs for and relevant health outcomes for wildfire. Oregon along with the rest of the western United States has seen a steady increase in wildfires in recent decades [2, 10]. Given the adverse health outcomes associated with wildfires and the projected increase in wildfire incidence in the future, it is important to understand the factors associated with wildfire incidence to try and help mitigate these effects.

Methods

Data Collection

Fire presence data were downloaded in both polygon and point shapefiles from the Monitoring Trends in Burn Severity (MTBS) project conducted by the U.S. Geological Survey National Center for Earth Resources Observation and Science (EROS) and the USDA Forest Service Remote Sensing Applications Center (RSAC). The polygon and point shapefiles were overlaid in ArcGIS 10.3.1 [45] and joined by the variable Fire ID (ID given to fires by the Department of Forestry in Oregon) to obtain complete information regarding fire perimeter, area (square meters), ignition date, agency (federal or state land), and fire type (prescribed burn, wildfire etc.). Only fires categorized as wildfires (WF) were selected and exported as a new shape-file (N=607) for analysis. Data relating to fire cause (anthropogenic vs. environmental) were obtained from the Federal Fire Occurrence website (http://wildfire.cr.usgs.gov/firehistory/data.html). Fire cause data were spatially merged with fire presence data and validated both manually and through R [46] to ensure fires were matched appropriately to each other.

Precipitation and temperature (average, maximum, and minimum) values were collected daily from 1984 to 2014. Data were downloaded and collected from the National Oceanic and Atmospheric Association (NOAA) Global Historical Climatology

Network stations (GHCN) for all of Oregon (ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/daily/). GHCN stations were mapped in ArcGIS and fires were spatially mapped to the closest station containing data for the fire ignition date. Precipitation is expressed in millimeters while temperature is expressed in Celsius degrees. Average weekly precipitation was calculated according to the International Organization for Standardization (ISO) weeks. Cumulative temperature values were calculated in R for each day using the following formula.

$$\frac{Tmax - Tmin}{2} - 10$$

Land-cover data were derived from the National Landcover Database (NLCD) and downloaded from the Multi-Resolution Land Characteristics Consortium (MRLC) (http://www.mrlc.gov/finddata.php). Data were obtained at 30 m spatial resolution for the United States for 1992, 2001, 2006, and 2011. The NCLD data were reclassified and clipped for the state of Oregon in ArcGIS. Land cover classes were reclassified into 6 categories: (1) grassland, (2) shrub-land, (3) deciduous forest, (4) evergreen forest, (5) mixed forest, (6) other. Fires from 1984 – 1996 were assigned the 1992 classifications, fires from 1997 - 2003 used the 2001 classification set, fires from 2004 to 2008 used the 2006 classifications, and the fires from 2007 – 2014 were assigned the 2011 land cover classifications. Fire data were overlaid with the NLCD data and using the extract values to points function in ArcGIS, NLCD classifications were assigned to each fire.

The remaining variables of interest, elevation, censal and intercensal population estimates, and distance to roads were collected and assigned to fires based on geographic location. Specific details on collections and transformation can be found in appendix I.

Wildfire absence (control) data was created using random point selection in ArcGIS. Fire perimeters spanning the study period were clipped from the study area and 607 random points were created within this new area. Wildfires and absence, or control, points were entered into data randomization software and matched. Each control point was attributed temperature and precipitation data that was a 10-year average of the decade the corresponding fire fell into (E.g. matched fire year = 1996, control data = average 1994-2003). Control points were given an SPEI index of 0, as that is considered average, or normal. Remaining variable values (elevation, slope, distance to nearest road, and population estimate) were assigned to control points based on year and location.

Descriptive Analysis

A series of descriptive statistics were generated from these data. Fire incidence was plotted graphically and defined by cause (anthropogenic vs natural). Similar cloropleth maps were developed for wildfire location and extent to visualize the fire regime for the period of interest (Figure 2). Additional maps were created to visualize static environmental variables of interest (transportation, elevation, and slope) (Figure 3). Simple point density analysis was performed in ArcGIS to assess potential clustering of wildfires over time (Figure 4). Additional descriptive statistics were performed in R to describe and visualize the general relationship of potential predictor variables (mean, median, standard deviation, and histograms) (Figure 5).

Univariate Analysis

Univariate logistic regression models were run for all the explanatory variables (Table 3) to evaluate their individual influence of the outcome variable (wildfire) and to determine the direction and value of those relationships, independent of the other variables of interest. To determine if the explanatory variables affected wildfire incidence differently than what would be expected by chance, 607 control locations were randomly selected throughout the study area. 607 controls were selected to mimic the number of wildfires within the study.

Analysis of Variance (ANOVA)

One-way ANOVA was run across the fires spanning three decades 1984 – 1993, 1994 – 2003, and 2004 – 2014. ANOVA tests were run to assess if any of the selected predictors exhibited variation over time. An additional ANOVA test was run comparing fires by cause, natural, anthropogenic, and control to assess determine if any predictors showed significant differences across fires based on cause.

Results

Descriptive Analysis

Wildfires (all)

Wildfires are present throughout the study area of interest and exhibit spatial variation (Figure 2). Wildfire counts and area burned shows an increasing trend over time (Figure 6). There is a slight clustering of wildfires in the study area as confirmed by Moran's I ($Z = 3.0897$ and $P = 0.002$). Based on the preliminary assessment of the point density analysis there are a few high-density pockets for wildfires in the southeast and middle portions of the state. When these fires are subdivided by cause, there is a high density of human caused fires in the middle portion of the state, whereas there are high density areas in the middle and southeast of naturally caused fires (Figure 4).

Temperature was assessed in four ways, cumulative temperature, average daily temperature, daily maximum, and daily minimum. All temperature metrics varied both spatially and temporally. Cumulative temperatures for wildfires ranged from 0 to 460.6, with the median at 49.4. Average temperature ranged from 3.3 °C to 35.3 °C with a median at 22.5 °C. Daily maximum temperature ranged from 0.3 - 45.6 °C with 50% of fires falling between 10.3 and 33.30°C. Daily minimum temperature ranged from -4.5 to 25 °C, with 50% of fires falling between 22.5 and 35.3 °C. Additionally, average weekly precipitation patterns varied temporally from 0 cm to 7.99 mm with a median of 0 mm.

Topographic variables of wildfire location, such as elevation, slope, and land cover type exhibit spatial variation. Fire elevation ranges from 203 – 7737 feet with 50% of fires occurring between 4210 and 7737 feet. Slope ranges from 0 to 430.53 percent increase with 50% of fires occurring between 0 and 53.13 percent increase. Oregon land coverage was divided into, grassland, shrub land, coniferous forest, deciduous forest, mixed forest, and other with 58% of all wildfires occurring in shrub land.

Social variables, including distance to roads and population density varied both spatially and temporally. Distance to the nearest road (from fire ignition location) ranges from 1.807 – 8606.03 meters with a majority of fires occurring between 0 and 500 meters from a road. Additionally, population estimates for the counties of fire ignition range from 1375 – 598286 people, with 50% of fires occurring in counties with populations between 7335 and 31303 people.

<u>Wildfires (anthropogenic vs. natural)</u>

Natural (n= 448) and anthropogenic (n=159) wildfires are present throughout the study area, with naturally occurring wildfires showing potential clustering in the southeastern portion of the state and anthropogenic induced fires clustering in the mid-western portion of the state. Natural fires show an increasing trend in numbers and area burned over time (Figure 7), where as anthropogenic fires show a decreasing trend in area burned and numbers over time (Figure 8).

All climate variables (drought, average daily temperature, maximum daily temperature, and minimum daily temperature, cumulative temperature, SPEI, and average weekly precipitation) showed variation across fire cause. Average temperature on fire days ranged from 7.7 - 35.3 °C for natural fires (median 22.8 °C) for natural fires and from 3.3 to 31.9 °C (median 21.4 °C) for anthropogenic fires. Maximum daily temperature ranged from 13.9 to 45.6 °C (median 33.9 °C) for natural fires, and ranged from 10.3 to 45 °C (median 31.2 °C) for anthropogenic fires. Minimum daily temperature ranged fro m-0.2 to 25.0 (median 12.2) for natural fires and -4.5 to 23.3 (median 10) for anthropogenic fires. Cumulative temperature ranged from 0.00 to 319.15 (median 54.92) for natural fires and from 0 – 460.55 (median 40.5) for anthropogenic fires. Drought indices ranged from -1.949 to 2.07 for natural fires (median -0.375) and -1.881164 to 2.119743 (median -0.686) for anthropogenic fires. Average weekly precipitation ranged from 0 to 7.986 mm (median 0 mm) for natural fires and from 0 – 3.86 mm (median 0 mm) for anthropogenic fires.

Topographic variables of wildfire location, such as elevation, slope, and land cover type exhibit spatial variation between fire causes. Elevation for natural fires ranged from 347 – 7737 feet (median 4328 feet), while anthropogenic fie elevation ranged from 203 – 7199 feet (median 3524). Slope ranged from 0 – 349.36 percent rise (median 51.28) for natural fires and from 0 – 439.53 percent rise (median 72.09) for anthropogenic fires. Concerning land cover, 47.7% of anthropogenic fires and 61% of natural fires occur on shrub land.

Social variables, including distance to roads and population density varied with fire cause. Distance to the nearest road (from fire ignition location) ranges from 0 – 349.36 meters (median 51.28) for natural fires and from 0 – 430.53 meters (median 72) for anthropogenic fires. Nearby population estimates for natural fires ranged from 1375 – 376891 people (median 21750 people), while natural fires ranged from 1411 – 598286 people (median 21770 people).

Analysis of Variance (ANOVA)

Results from ANOVA analysis showed that drought and cumulative temperature differed between the three decades of interest (Table 4). Looking at drought results indicate that drought levels associated with fires were greater in decade 2 and decade 3 than decade 1. Additionally, cumulative temperature was on average greater in decade one compared to decade 2 and decade 3.

ANOVA analysis comparing anthropogenic, natural, and control fires showed SPEI, maximum daily temperature, minimum daily temperature, elevation, slope, weekly precipitation, distance to nearest roads, and population differed between groups (Table 5). Anthropogenic fires occurred in conditions of greater drought and percentage slopes rise, than control and naturally occurring fires. Naturally occurring fires transpired in regions with higher: maximum daily temperature, minimum daily temperature, and elevation. Both naturally and anthropogenic induced fires occurred at greater distances to roads and in areas with lower precipitation than controls.

Univariate Analysis

Simple logistic regressions were run for each variable of interest to determine their potential suitability as predictors for wildfire in the region (Table 6). Additional regressions were run to determine differences between natural (Table 7) and anthropogenic (Table 8) caused fires.

<u>Fire vs. Control</u>

Initial tests were run to explore possible predictors for wildfires, using wildfire as the reference (compared to no fire). When looking at the complete data set, minimum temperature (OR 1.144, CI 1.111 – 1.178), maximum daily temperature (OR 1.134, CI 1.107 – 1.163), grass land cover (OR 2.034, CI 1.337 – 3.095), and shrub land cover (OR 1.958, CI 1.58 0 2.494) showed positive relationships with fire; where as SPEI (OR 0.47, CI 0.384 – 0.572) average weekly precipitation (OR .087, CI 0.064 – 0.12), other land cover (OR 0.441, CI 0.288 – 0.674), evergreen forest (OR .554, CI 0.432 – 0.711), deciduous forest (OR 0.075, CI 0.01 – 0.578), and mixed forest (OR .262, CI 0.086 – 0.793) showed negative relationships.

<u>Anthropogenic vs. Natural Fire</u>

When data was subdivided between natural and anthropogenic fires, the strength and relationship of variables shifted. For natural fires, compared to anthropogenic fires, SPEI (OR 1.339, CI 1.07 -9 – 1.673), average daily temperature (OR 1.116, CI 1.071 – 1.165), daily minimum temperature (OR 1.123, CI 1.079 – 1.172), average weekly precipitation (1.382), and shrub land (OR 1.752, CI 1.217 0 2.527) present a positive relationship. Where as slope (OR 0.997, CI 0.995 – 0.1), other land cover type (OR

0.374, CI 0.186 – 0.760), deciduous forest (OR 0.783, CI 0.519 – 1.184) showed a positive relationship to fire ignition.

When comparing fire cause to controls the predictors and their change shifted again. Comparing naturally occurring fires to control fires, grassland (OR 2.034, CI 1.337 - 3.095) and shrub land (OR 1.985, CI 1.58 – 2.494) showed a positive relationships with fire incidence, while SPEI (OR 0.47, CI 0.384 – 0.571), average weekly precipitation (OR 0.087, CI 0.064 – 0.12), other land coverage types (OR 0.441, CI 0.288 – 0.674), coniferous forest (OR 0.075, CI 0.01 – 0.578), deciduous forest (OR 0.54, CI 0.43 – 0.711), and mixed forest (OR .262, CI 0.086 – 0.793) showed negative relationships. In contrast, when comparing anthropogenic wildfires SPEI (OR 0.074, CI 0.043 – 0.123), average weekly precipitation (OR 0.005, CI 0.002 – 0.01), and deciduous forest (OR 0.664, CI 0.452 – 0.975) showed negative relationships.

Discussion

Both the Intergovernmental Panel on Climate Change and National Climate Assessment have identified the possibility for an increase in the potential for wildfires occurring as a result of a changing climate [47]. The changes in wildfire will likely be the result of expanding insect ranges, increased temperatures, and changes in drought. The purpose of this study was to explore the relationship between regionally specific variables and wildfire incidence in the region, and how these variables change over time and with wildfire cause.

Initial exploration of wildfires in Oregon (1984 – 2014) has shown an increasing trend in both wildfire numbers and extent (Figure 6). When fires are subdivided by cause, the trend of increasing extent and count is maintained for natural wildfires, but reverses for anthropogenic wildfires. Given that fire spread and ignition is a function of vegetation characteristics, climate, and topography it was estimated that the environmental variables would have a strong influence on fire incidence (sources). As expected, a majority of fires occurred in areas with lower average weekly precipitation, more severe drought indices, higher daily maximum and minimum temperatures, and in shrub lands. Accordingly, several environmental variables: maximum temperature, minimum temperature, land cover, drought (SPEI), and average weekly precipitation are proving to be significant predictors of wildfire incidence in the region. Further analysis of these variables and their relationship to wildfire over time indicate that there is an increase in drought levels along with wildfire levels over time (Table 4). This substantiates previous research on global and local scales, which concludes that climatic factors, due to their influence on fuel source availability and suitability are the primary influencers of wildfire extent [12].

Additional studies on natural and anthropogenic wildfire incidence have found that wildfire incidence can also be linked to human activities (social variables) due to their influence on ignition, frequency and fuel source availability and continuity [15, 22, 35] (Figure 1). Furthermore, studies stipulate that these social variables are stronger predictors than environmental variables for anthropogenic wildfires [22, 27]. Given that 74% of fires occurring in Oregon are natural in origin, it makes sense that social variables exhibit little predictive power for all fires in this region. Specifically, the natural fires far outnumber the anthropogenic fires limiting the influence of social variables for all fires combined. Furthermore, analysis comparing natural and anthropogenic wildfires again revealed that environmental variables are stronger predictors for natural wildfires than anthropogenic wildfire and social variables showed no predictive power for either. This is likely due to the more remote location of natural wildfires in Oregon, limiting anthropogenic interaction. While social variables such as distance to roads and population density were not significant ($p < 0.05$) in univariate analyses for all wildfires, natural wildfires, or anthropogenic wildfires, in Oregon, it is worth noting that on average, anthropogenic fires occurred in closer to proximity to roads than natural fires (Wilcoxon Two Sample test $p < 0.05$).

In summary, these data highlight that there is an increasing trend in naturally caused wildfires (over anthropogenic wildfires) and the ignition and extent of these natural fires are primarily determined by environmental variables. As climate models are predicting an increase in the environmental variables favorable for wildfire ignition and spread (higher temperatures, drought, and decreased precipitation) there is an increased likelihood of a spike in adverse health outcomes associated with wildfires. Accordingly, there is a need for enhanced understanding of the populations at risk for exposure to wildfires and wildfire smoke in the region.

Limitations

Potential limitations of this study relate to the assignment of variable values to fires and controls and the univariate analysis applied. The transportation map used to calculate distance to roads was based on a single time period while fires spanned a period of 30 years. As development in Oregon has increased over the 30-year time period it is possible that distances may not be accurate for all fires included. Additionally the assessments used in this study are based on univariate regressions, holding all other variables constant. It is possible that upon construction of a multivariate model that certain predictors previously not considered significant will become significant in coordination with other variables.

Future Research

This project served as the initial step in a larger project regarding fire risk in Oregon. Similar analysis will be covered including additional variables such as lightning strikes, housing density, and population density. Following the completion of this additional analysis, multivariate logistic regression models will be created to determine relevant variables for fire ignition prediction in the region. Upon completion of this model, wildfire risk maps will be developed for this region.

Conclusion

This study builds on existing literature relating environmental and social variables to wildfire incidence to gain a better understanding of the impact of these variables of wildfire incidence in Oregon. Preliminary assessment of several environmental and social variables show that a majority of wildfires in Oregon are natural in origin, show distinct clustering, and are related to temperature extremes, land cover, and drought. Environmental variables show promise as important predictors for wildfire occurrence in this region. The historic and projected rise in large naturally caused wildfires and will have substantial impacts on public health in the region. An increase in the frequency and extent of wildfires means a rise in communities threatened by displacement from flames as well as an increase in populations at risk for respiratory and cardiovascular disease associated with wildfire smoke. Accordingly there is a need for continued research in the realm of probability and risk mapping for wildfires and associated populations at risk in the region.

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Tables and Figures

Table 1. Summary Statistics: Fire cause

Summary statistics from the United States Department of Agriculture of wildfire causes in the United States from 2000 to 2008.

Cause	Average Annual Ignitions Reported	Average Annual Area Burned (acres)	Percentage Share of Reported Ignitions	Percentage Share of Reported Area Burned
Natural / Lightning	10,874	5,496,235	45.34	79.90
Campfire	1,964	179,338	8.19	2.61
Smoking	418	22,387	1.74	0.33
Fire Use / Debris Burning	1,538	100,971	6.41	1.47
Incendiary / Arsons	2,969	268,962	12.38	3.91
Equipment (Use)	1,338	246,804	5.58	3.59
Railroad	117	14,193	0.49	0.21
Juveniles / Children	1,063	20,464	4.43	0.30
Miscellaneous and Unknown	3,704	529,313	15.44	7.69

Table 2. Summary Statistics: Fire Cause by Region

Summary statistics from the United States Department of Agriculture of wildfire causes sub divided between the Eastern and Western United States.

Cause	Western Forest Service Regions		Eastern Forest Service Regions	
	Average Annual Fires	Percent by Cause	Average Annual Fires	Percent by Cause
Lightning	5255	65	193	11
Campfire	1116	14	116	7
Smoking	152	2	27	2
Debris / Burning	191	2	278	17
Arson	220	3	651	39
Equipment Use	258	3	62	4
Railroad	33	0	24	1
Children	65	1	21	1
Miscellaneous and Unknown	841	10	311	18

Table 3 Explanatory Variables

Selected variables of interest for wildfire prediction categorized as environmental or anthropogenic

Category	Variable	Source	Description
Environmental	Precipitation	NOAA / NCDC	Weekly average precipitation
	Temperature (avg, max, min)	NOAA / NCDC	Daily cumulative temperature (°C)
	Land Cover	MRLC / NLCD	Classification of land type
	Slope	USGS	Percent rise of slope
	Elevation	USGS	Elevation above sea level (ft)
	Drought	Global SPEI Database	
Social	Population Estimates	US Census Bureau	Annual population estimate by county
	Distance to Roads	Emory University	Distance from fire to nearest road (m)

Table 4. ANOVA Results: Decade

Significant ($p < 0.05$) results from ANOVA analysis comparing variables across decades. Decade one is 1984 – 1993, Decade 2 is 1994 – 2003, and Decade 3 is 2004 -2014

Variable	Decade 1		Decade 2		Decade 3		p-value
	n	Mean ± SD	n	Mean ± SD	n	Mean ± SD	
SPEI	174	0.1283 ± 0.9512	195	-0.4732 ± 0.8583	238	-0.4232 ± 0.7177	< .0001

Table 5. ANOVA Results: Fire Cause

Significant ($p < 0.05$) results from the ANOVA analysis comparing fires of different origins.

Variable	Controls		Natural Fires		Anthropogenic Fires		p-value
	n	Mean ± SD	n	Mean ± SD	n	Mean ± SD	
SPEI	607	0.000 ± 0.000	448	-0.23 ± 0.88	159	-0.44 ± 0.84	< .0001
Maximum Daily Temperature	607	28.88 ± 5.08	448	32.82 ± 5.01	159	30.84 ± 6.56	< .0001
Minimum Daily Temperature	607	9.31 ± 3.60	448	12.274 ± 4.45	159	9.82 ± 4.88	< .0001
Elevation	607	3481.62 ± 1749.88	448	4094.03 ± 1313.79	159	3630.81 ± 1678.56	< .0001
Slope	607	67.24 ± 69.52	448	77.172 ± 71.620	159	92.34 ± 84.69	0.0003
Average Weekly Precipitation	607	1.49 ± 1.38	448	0.31 ± 0.74	159	0.18 ± 0.58	< .0001
Distance to Nearest Road	607	597.78 ± 827.06	448	1061.03 ± 1118.56	159	882.16 ± 944.65	<.0001
Population	607	65856.48 ± 93417.34	448	34297.93 ± 50898.86	159	41059.36 ± 69934.40	<.0001

Table 6. Univariate Regression: All fire

Univariate regression results for all potential predictors for wildfire in Oregon (Wildfire compared to controls)

Explanatory Variable	Beta	Std. Error	P-value	Odds Ratio	95% CI	
					Lower	Upper
SPEI (drought)	-0.755	0.101	0.001	0.470	0.384	0.571
Elevation	0.000	0.000	<.0001	1.000	1.000	1.000
Slope	0.003	0.001	0.001	1.003	1.001	1.004
Cumulative Temperature	0.001	0.001	0.135	1.001	1.000	1.003
Minimum Temperature	0.134	0.015	<2e-16	1.144	1.111	1.178
Maximum Temperature	0.126	0.012	<2e-16	1.134	1.107	1.163
Average Weekly Precipitation	-2.439	0.161	<.0001	0.087	0.064	0.120
Distance to Nearest Road	0.001	0.000	<.0001	1.001	1.000	1.001
Population	5.81 E -6	0.071	<.0001	1.000	1.000	1.000
Other Land Types	-0.819	0.217	0.000	0.441	0.288	0.674
Grassland	0.710	0.214	0.001	2.034	1.337	3.095
Shrub land	0.685	0.117	<.0001	1.985	1.580	2.494
Coniferous Forest	-2.585	1.039	0.013	0.075	0.010	0.578
Deciduous Forest	-0.590	0.127	<.0001	0.554	0.432	0.711
Mixed Forest	-1.340	0.566	0.018	0.262	0.086	0.793

Table 7. Univariate Regression: Natural Fire

Univariate regression results for all potential predictors for natural wildfires in Oregon (natural wildfires compared to controls)

Explanatory Variable	Beta	Std. Error	P-value	Odds Ratio	95% CI	
					Lower	Upper
SPEI (drought)	-0.709	0.117	0.000	0.492	0.389	0.617
Elevation	0.000	0.000	<.0001	1.000	1.000	1.000
Slope	0.002	0.001	0.024	1.002	1.000	1.004
Cumulative Temperature	0.001	0.001	0.103	1.001	1.000	1.003
Minimum Temperature	0.188	0.018	<2e-16	1.206	1.166	1.250
Maximum Temperature	0.169	0.015	<2e-16	1.184	1.149	1.221
Average Weekly Precipitation	-2.537	0.182	<.0001	0.079	0.055	0.113
Distance to Nearest Road	0.001	0.000	<.0001	1.001	1.000	1.001
Population	0.000	0.078	<.0001	1.000	1.000	1.000
Other Land Types	-1.168	0.271	<.0001	0.311	0.183	0.529
Grassland	0.667	0.229	0.004	1.948	1.243	3.051
Shrub land	0.836	0.128	<.0001	2.307	1.797	2.962
Coniferous Forest	-14.955	564.500	0.979	<0.001	<0.001	>999.999
Deciduous Forest	-0.658	0.140	<.0001	0.518	0.393	0.682
Mixed Forest	-1.730	0.755	0.022	0.177	0.040	0.778

Table 8. Univariate Regression: Anthropogenic Fire

Univariate regression results for all potential predictors for anthropogenic wildfires in Oregon (anthropogenic wildfires compared to controls)

Variable	Beta	Std. Error	P-value	Odds Ratio	95% CI	
					Lower	Upper
SPEI (drought)	-2.600	0.267	<2e-16	0.074	0.043	0.123
Elevation	0.000	0.000	0.335	1.000	1.000	1.000
Slope	0.004	0.001	0.000	1.004	1.002	1.006
Cumulative Temperature	0.001	0.001	0.566	1.001	0.998	1.003
Minimum Temperature	0.033	0.023	0.148	1.034	0.988	1.081
Maximum Temperature	0.074	0.019	0.000	1.077	1.039	1.119
Average Weekly Precipitation	-5.402	0.411	<.0001	0.005	0.002	0.010
Distance to Nearest Road	0.000	0.000	0.000	1.000	1.000	1.001
Population	0.000	0.000	0.002	1.000	1.000	1.000
Other Land Types	-0.185	0.292	0.527	0.831	0.469	1.473
Grassland	0.825	0.295	0.005	2.282	1.281	4.065
Shrub land	0.275	0.179	0.124	1.317	0.927	1.870
Coniferous Forest	-1.239	1.041	0.234	0.290	0.038	2.228
Deciduous Forest	-0.410	0.196	0.037	0.664	0.452	0.975
Mixed Forest	-0.688	0.758	0.364	0.503	0.114	2.222

Figure 1. Causal Pathway

Pathway depicting inputs necessary for wildfire occurrence and the health outcomes associated with wildfires.

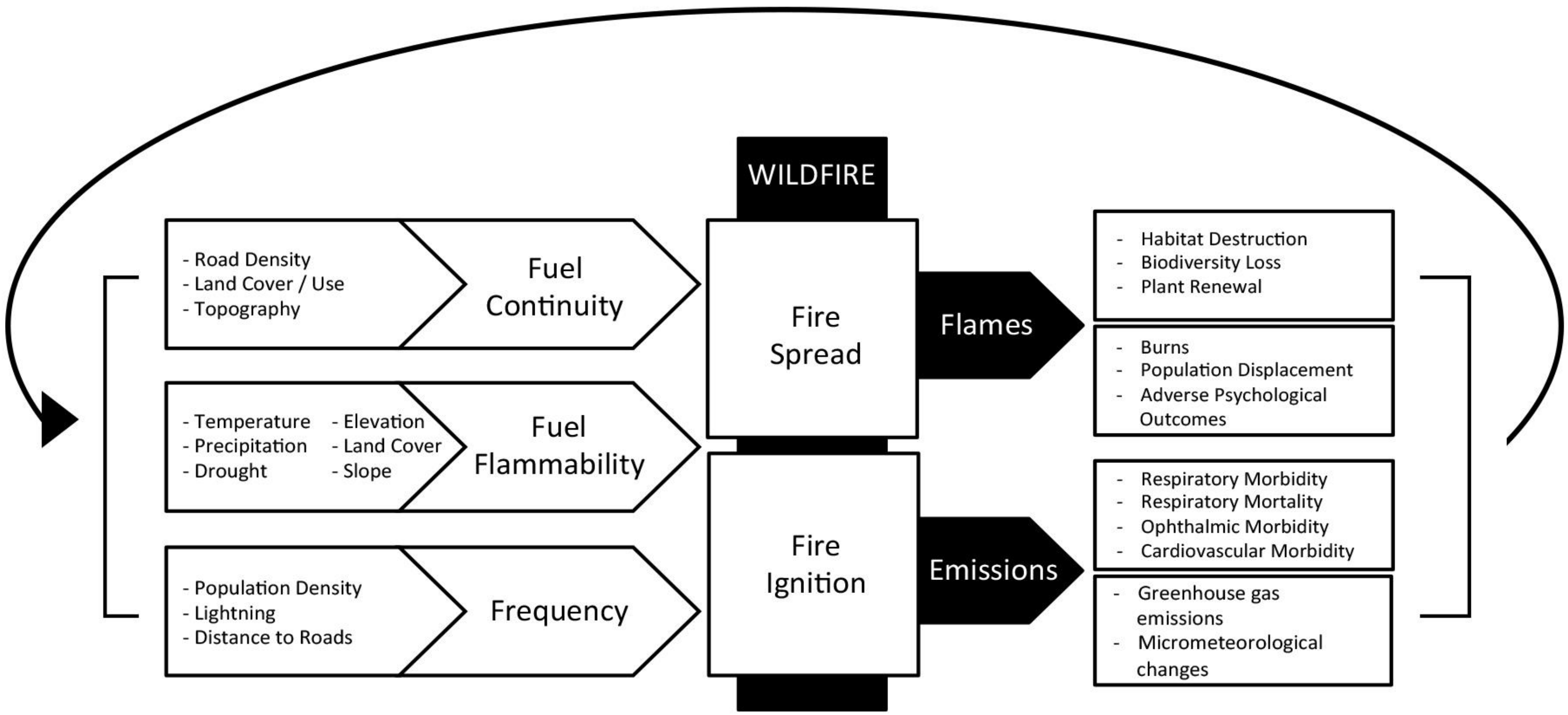


Figure 2. Oregon Wildfires

Two maps depicting Oregon Wildfires greater than 900 acres from 1984 to 2014. The upper map is all wildfires and the lower map divides wildfires by cause (anthropogenic and natural).

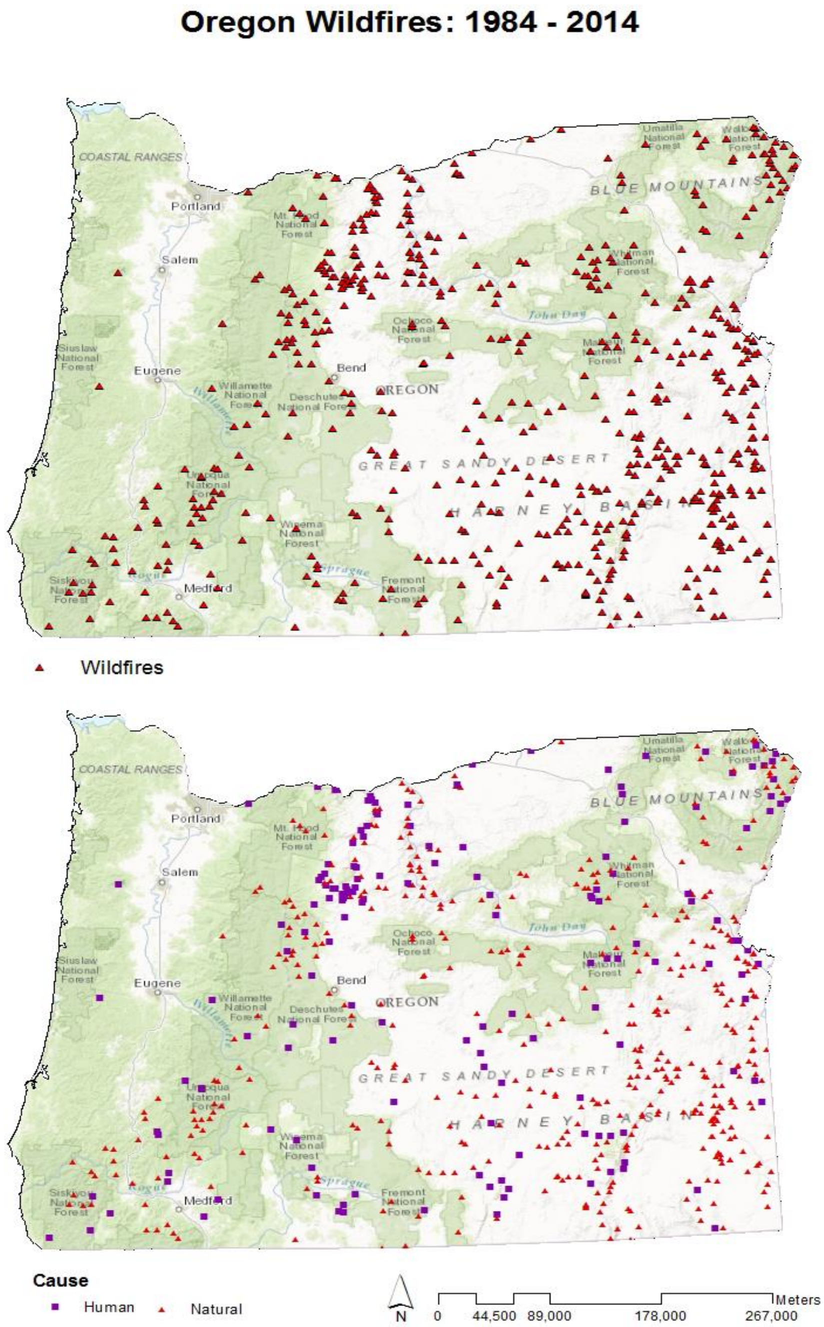


Figure 3. Static Variables of Interest

Four maps depicting variables of interest that are not adjusted to change over time, fire ignition location, transportation, elevation, and slope.

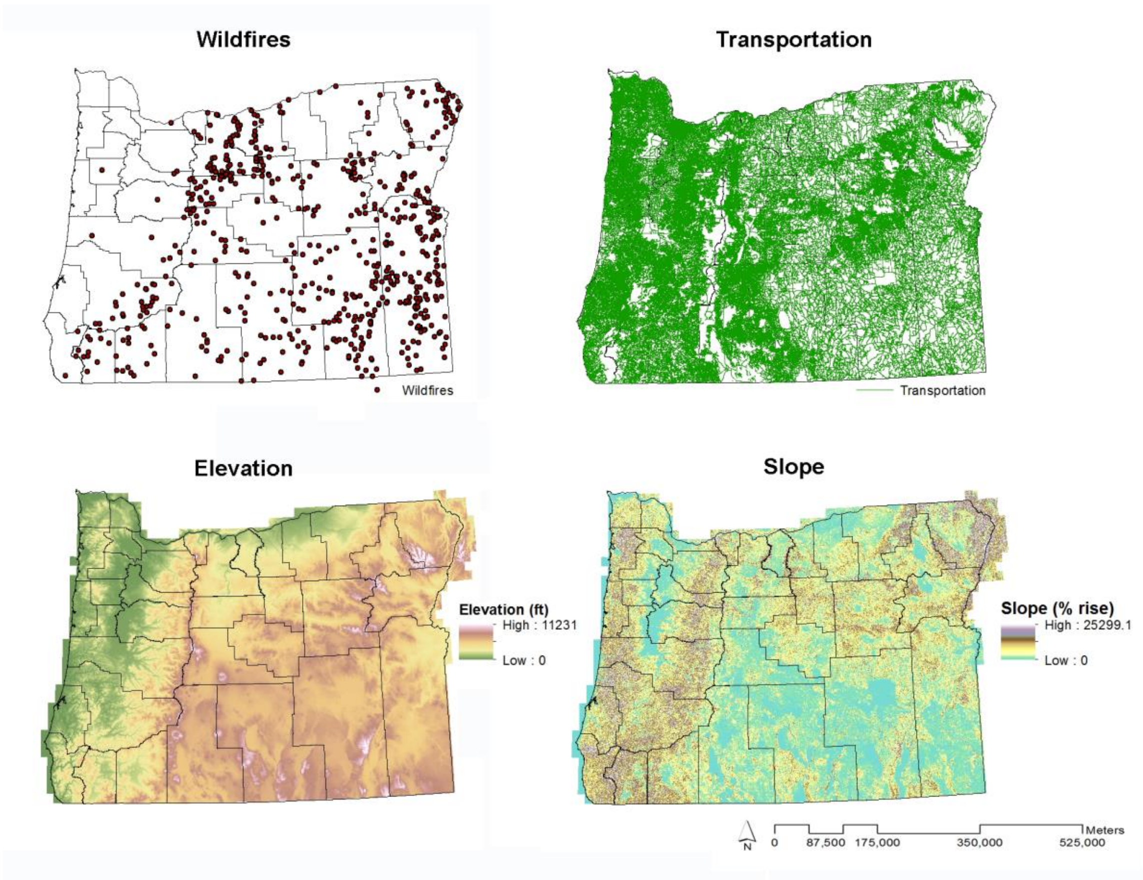


Figure 4. Point Density Maps

Maps depicting point density analysis of wildfires in Oregon. The far left map is all fires, the middle map represents natural fires and the lower map represents anthropogenic fires.

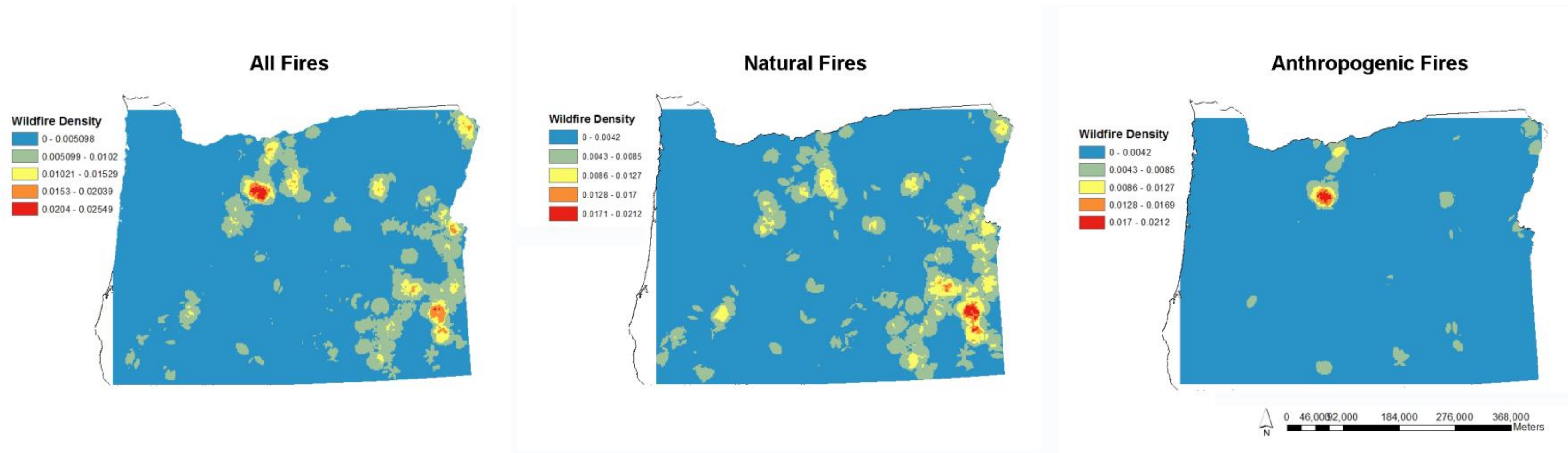


Figure 5. Explanatory Variable Histograms

Histograms of all explanatory variables for wildfires. Red dashed lines indicate individual quintiles for the variable.

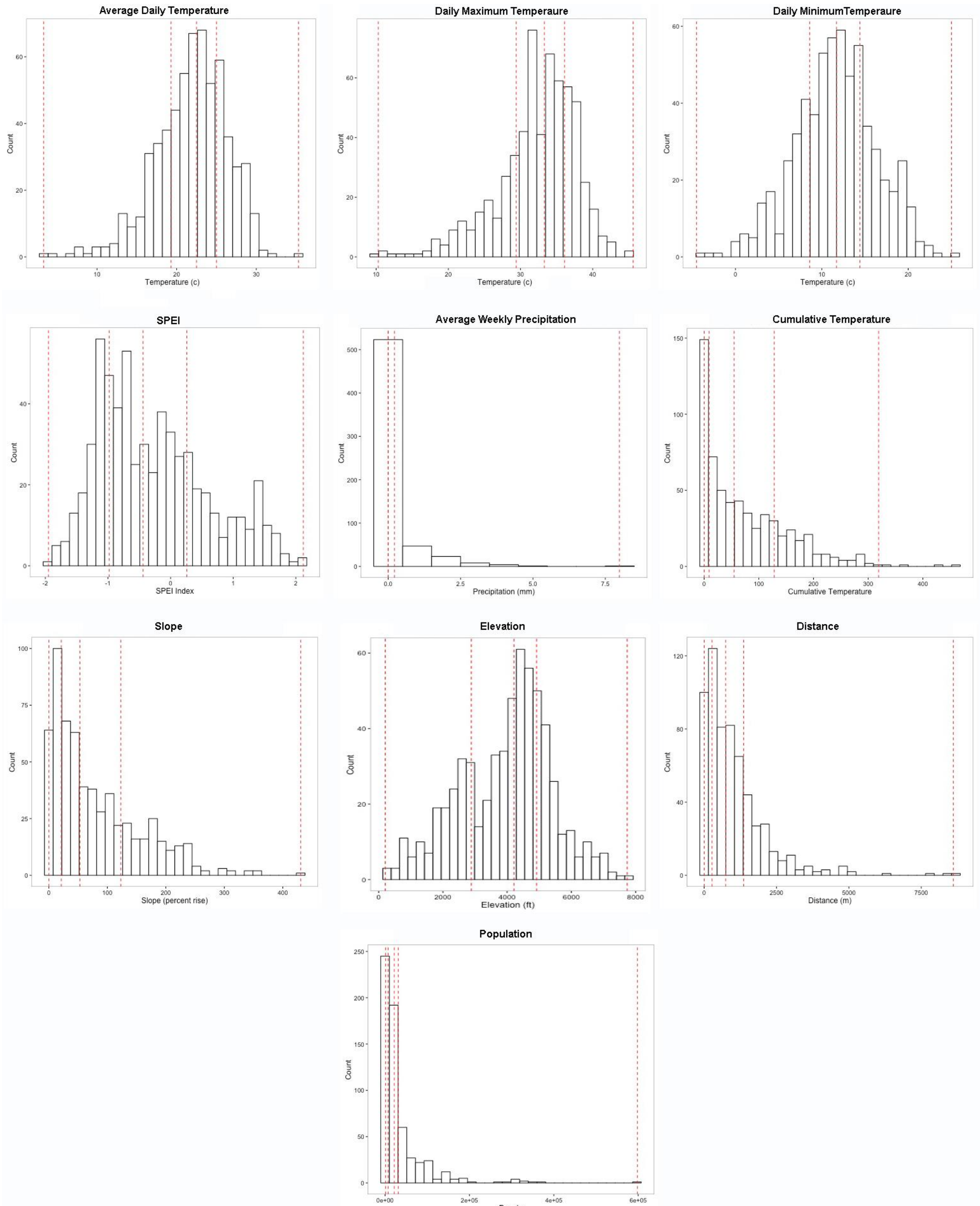


Figure 6. Wildfire Numbers and Extent

Wildfire numbers and acres burned over time: Graph depicts the number of wildfires per year along with the area burned over time in m2. The axis on the left depicts wildfire counts and axis on the right depicts the area burned.

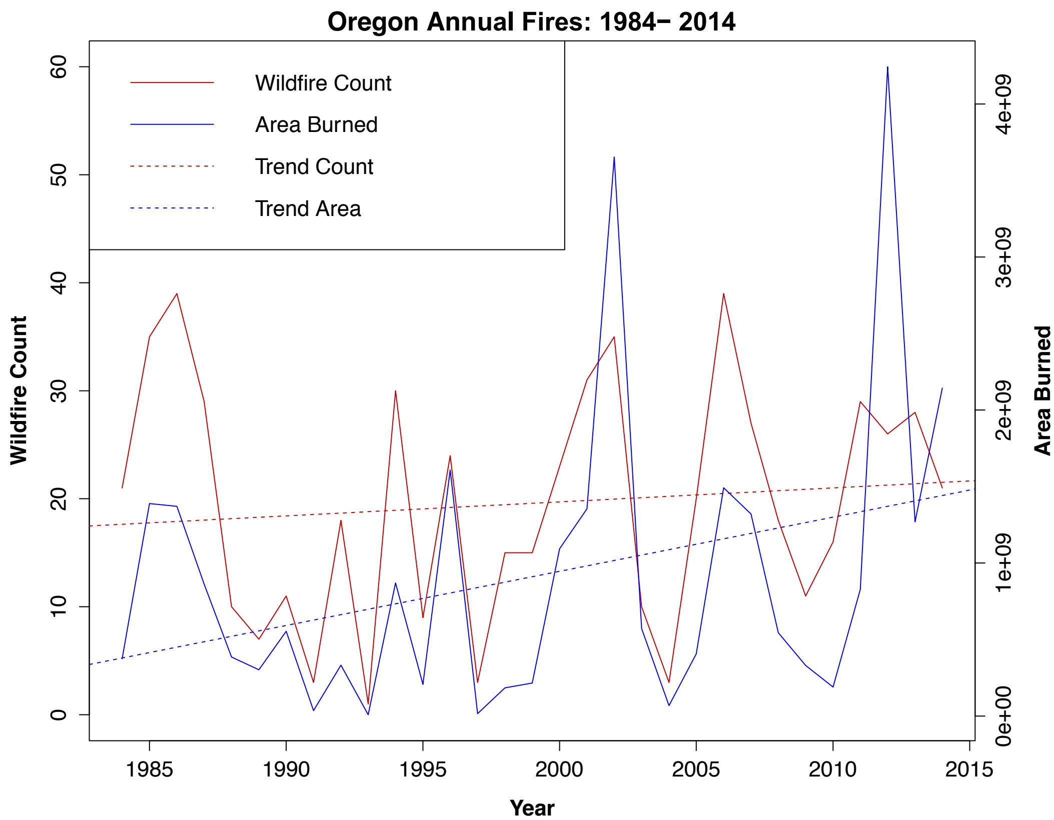


Figure 7. Natural Wildfires: Count and Extent

Graph depicting wildfire count and area burned over time, for naturally occurring fires during the study period.

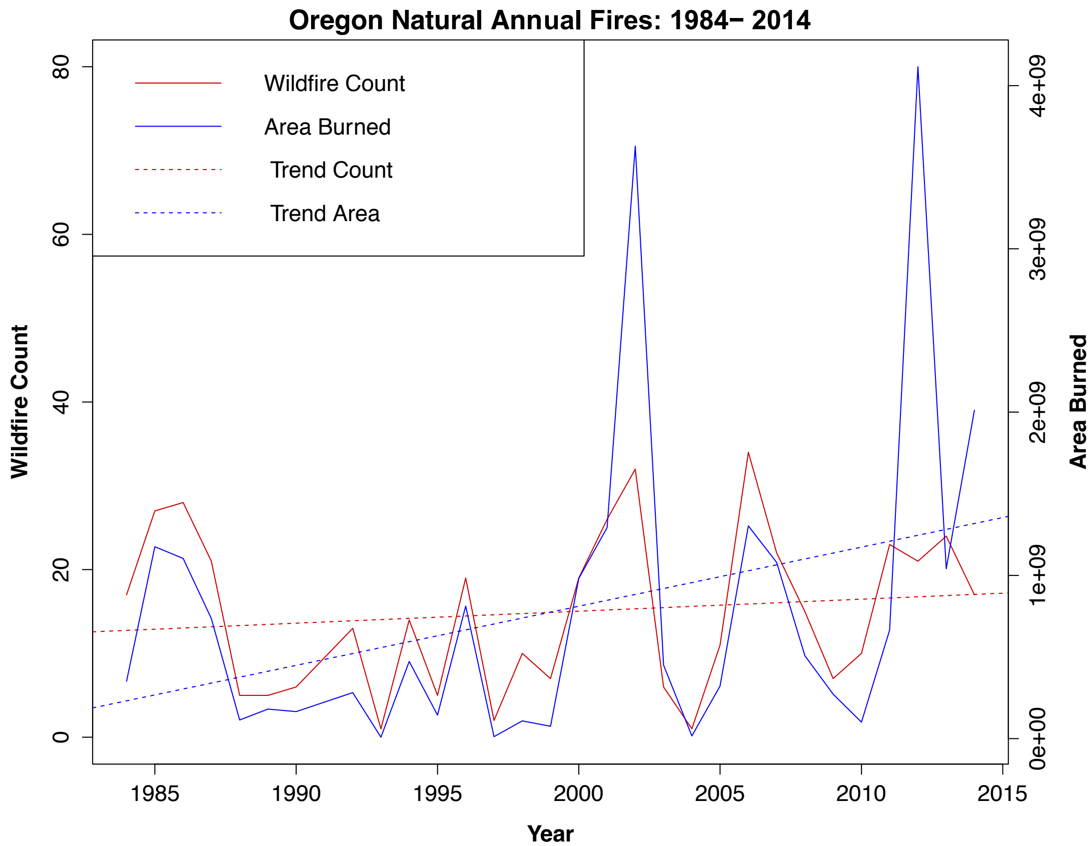
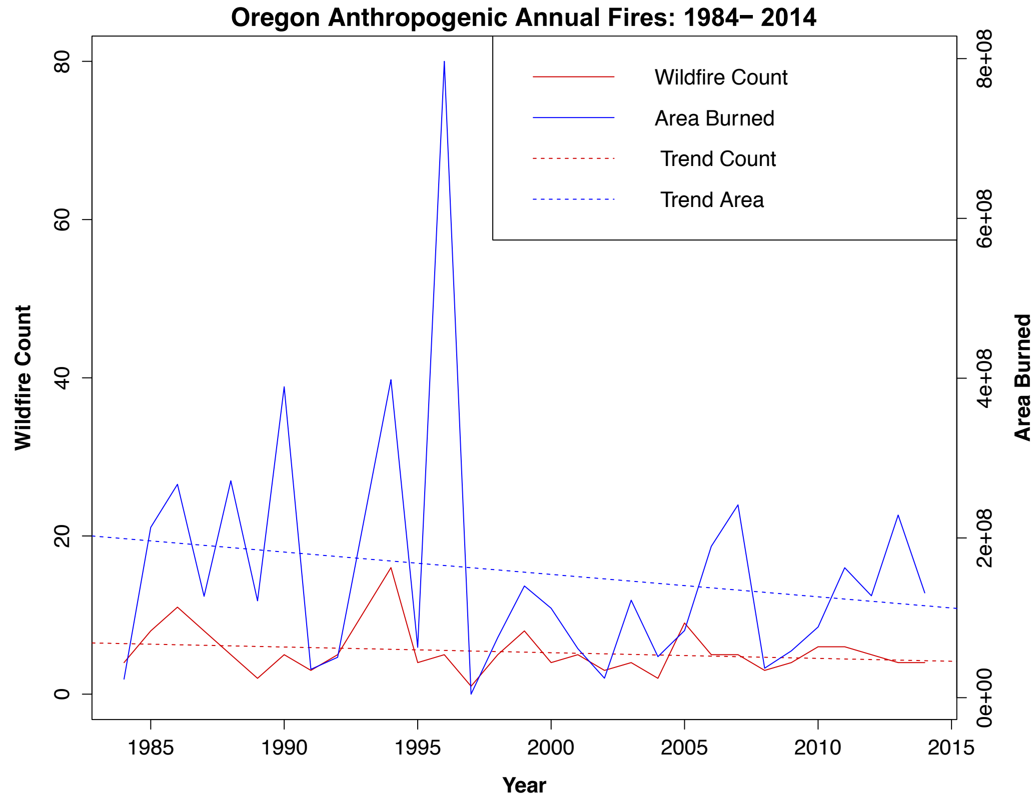


Figure 8. Anthropogenic Wildfires: Count and Extent

Graph depicting wildfire count and area burned over time, for anthropogenic fires during the study period.



Appendices

Appendix I

Elevation data for the state of Oregon were obtained from the Oregon Geospatial Clearinghouse website (http://www.oregon.gov/geo/Pages/sdlibrary.aspx) . Digital elevation maps (DEM) were downloaded at 10m spatial resolutions in nine pieces covering the state of Oregon. All DEM files were uploaded into ArcGIS and merged by mosaic to create a continuous elevation file for the state. Fire ignition locations were overlaid with the elevation map. Elevation values were extracted and assigned to the overlaid ignition locations. Percentage slope was calculated in ArcGIS using the continuous elevation map. Percentage slope values were assigned to fires based on ignition location.

Censal and intercensal annual population estimates were obtained from the United States Census Bureau for each county in Oregon from 1984 -2014. Fires were matched to county of origin and assigned a population estimate based on the assigned county and year of fire ignition.

Transportation data was obtained through Emory University. Transportation maps including, roads, highways, and train tracks were overlaid with fire ignition data. Distance to nearest transportation point was calculated in ArcGIS using the spatial merge function. Distances were recorded in meters.

State and County Shapefiles created using Geographic Coordinate System (GCS) North America 1983 and were projected in ArcGIS to North America 1983 Universal Transverse Mercator (UTM) Zone 10N. The projected Oregon state shapefile was used as the extent for the study.