The influence of climate change on California wildfires and type of vegetation burned

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Figure 1 - Credit Kent Porter/The Press Democrat, via Associated Press

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Samenvatting

Sinds de jaren 1980 is de activiteit van grote bosbranden in Californië gestegen. Deze trend is nog steeds zichtbaar. De oorzaak van deze stijging is niet duidelijk. Deze scriptie focust zich of het verband tussen klimaatverandering en de verbrande oppervlakte in Mariposa County, California, en het type verbrande vegetatie. De onderzoeksvraag van deze scriptie is: **“Hoe is de omvang van de door bosbranden verbrande oppervlakte en het type verbande vegetatie, gecorreleerd aan klimaatverandering in Mariposa County?”** Californië data (bosbrand frequentie en omvang verbande oppervlakte) is gebruikt om een regionale trend waar te nemen. Daarna is Mariposa County data geanalyseerd om lokale trends in bosbranden waar te nemen. Ook de invloed van weerpatronen op de omvang van de verbrande oppervlakte en type verbrande vegetatie is onderzocht. Bosbrand data (omvang verbrande oppervlakte en type verbrande vegetatie) en gemiddelde jaarlijkse weerdata (maximumtemperatuur, minimumtemperatuur en neerslag) in Mariposa County is gebruikt over een periode van 1950 tot 2013. Statistische analyses zijn uitgevoerd waarbij gebruik is gemaakt van Pearson correlaties.

De hoofdzakelijke bevindingen worden kort samengevat: een significante stijging in verbrande oppervlakte in Mariposa County en Californië is gevonden. De invloed van klimaatverandering op de Mariposa County weerdata is minder duidelijk. De gemiddelde jaarlijkse minimumtemperatuur laat een significante stijging van 1.5 graden Celsius zien in de periode van 1950 tot 2013. De maximumtemperatuur en neerslag laten geen significante verandering zien over die periode. Verder is er geen directe significante correlatie gevonden tussen weerdata en de omvang van de verbrande oppervlakte of type verbrande vegetatie. Een indirecte correlatie tussen het 9-jarig voortschrijdend gemiddelde van oppervlakte verbrand bosland en minimumtemperatuur is wel gevonden (Pearson’s $r = 0.829$, $p < 0.01$). Deze stijging in oppervlakte verbrand bosland zou veroorzaakt kunnen worden door een stijging in minimumtemperatuur. De stijging van de minimumtemperatuur kan het gevolg zijn van klimaatverandering. Samengevoegd zou de stijging in oppervlakte verbrand bosland veroorzaakt kunnen zijn door klimaatverandering.

Trefwoorden: bosbrand, klimaatverandering, Californië, vegetatie

Abstract

Large California wildfire activity increased suddenly in the mid-1980's and has been increasing ever since. The cause of this increase has not been clear. This thesis focuses on the correlation between number of acres burned in Mariposa County, California, and the type of vegetation burned under the influence of climate change. The research question is:

"How are the number of acres burned by wildfires and type of vegetation burned connected to climate change in Mariposa County?"

California data (wildfire frequency and number of acres burned) has been used to determine regional trends in acres burned. Thereafter, Mariposa County data has been analyzed to determine local trends in wildfire and the influence of weather on number of acres burned and type of vegetation burned. Wildfire data (number of acres burned, and type of vegetation burned) and average annual weather data (maximum temperature, minimum temperature and precipitation) in Mariposa County over a period of 1950 to 2013 have been used. Statistical analyzes using Pearson Correlations were performed.

The main findings of the research are summarized as followed: first, a significant increase in Mariposa County and California area burned due to wildfires is found in the data. The influence of climate change on the weather in Mariposa county is less clear. The average annual minimum temperature shows a significant increase of over 1.5 degrees Celsius in the period of 1950-2013. The maximum temperature and precipitation do not show such a trend. Furthermore, no significant direct correlation between weather patterns and number of acres burned or type of vegetation burned has been found. A more indirect correlation between 9-year moving averages of woodland area burned and minimum temperature could be found (Pearson's $r = 0.829$, $p < 0.01$). If there is a causality, the increase in woodland area burned in Mariposa County could be caused by an increased minimum temperature. This increase in minimum temperature could be caused by climate change. Therefore, the increase in woodland area burned in Mariposa County could have been possibly caused by climate change.

Keywords: wildfire, climate change, California, vegetation

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1 Introduction

Large California wildfire activity increased suddenly in the mid-1980's and has been increasing ever since (Westerling, Hidalgo, Cayan, & Swetnam, 2006). 2017 has been a record year, having five of the ten most damaging wildfires in the recorded history (Flavelle, 2018). Large wildfires increase not only in frequency but last longer too, as well as the wildfire seasons (Rocca, Brown, MacDonald, & Carrico, 2014).

The increase in wildfires is a social problem; human lives are being increasingly threatened since more people are living in fire country (Flavelle, 2018; Westerling et al., 2006). This results not only in lives being lost, but also in millions of homes and properties being ruined (Westerling & Bryant, 2007). Therefore, it is an economic problem as well. Based on this, the problem definition used in this thesis is: **"The increase in frequency and intensity of California wildfires is threatening human lives and damaging properties"**. The cause of this increase is unclear (Hurteau, Bradford, Fulé, Taylor, & Martin, 2014; Kenzie, Gedalof, Peterson, & Mote, 2004), but is influenced by several factors such as direct human intervention, type of vegetation, climate and weather conditions (See appendix Figure 17) (Westerling et al., 2006). This thesis will specifically focus on the increase in number of acres burned and type of vegetation being burned under the influence of climate change.

1.1 Direct human intervention

Since more people are living in fire country (Flavelle, 2018), small fires have been extinguished by the California fire department (CalFire) instead of burned out naturally (Busenberg, 2004). Wildfires are a natural phenomenon; many native plant species in wildfire country are adapted to the high temperatures and native animals are able to escape the fire (Pausas, Llovet, Anselm, & Vallejo, 2008; Shaffer & Laudenslayer, Jr., 2006). But fires threaten the people and their properties. Therefore, most fires get extinguished. Small fires should burn smaller plants and dead wood, which is fuel for wildfires (Westerling & Bryant, 2007). Since this fuel is not burned by the small fires, it accumulates. Once a bigger fire erupts that cannot be controlled by the fire department, a lot of fuel is available. This results in bigger and more aggressive fires that not only burn the dead wood and smaller plants but also affect the bigger vegetation like trees, that otherwise would not catch flame (Busenberg, 2004). Fire treatment policy was reinforced in the period of 1905 until 1960 in all of the United States and did not include a program to respond to the accumulation of fuels. This has resulted in a decrease in the wildfire frequency in the beginning of the 20^{th} century. But the fuel accumulation that accompanies this decrease (Hurteau et al., 2014), results in a greatly increased risk of damaging, high-intensity wildfires in American wildlands, like California for the years afterwards (Busenberg, 2004). Another intervention of humans is the planting of less fire resilient vegetation, like fire-sensitive pine woodlands (Pausas et al., 2008). This results in more flammable woods, which causes more wildfires as well. This land-use history has been the main focus of previous wildfire research literature (Westerling et al., 2011).

If an increase in wildfire frequency is primarily driven by land-use history and the accumulation of fuel, then ecological restoration and fuel management could be the solution to mitigate the increase in wildfire. Yet, it is not only direct human intervention that causes these wildfires. It is expected that human induced climate change also influences the process of increased fire frequency (Westerling et al., 2006). This topic will be examined in the next paragraph.

1.2 Climate change and burned vegetation

California is one of the most climatically and biologically diverse areas in the world (Lenihan, Drapek, Bachelet, & Neilson, 2003). The state has arid ecosystems dominated by grass and brush vegetation and deserts with no vegetation. In these regions a period of more than average precipitation in spring could result in more small plant growth. If this wet period is followed by an arid period with higher temperatures in summer, these newly grown small plants will dry out. The dry plants are great fine-fuels for wildfires (Turco et al., 2017). This mechanism is mostly found in arid areas in south California, where a lack of precipitation limits the growth of plants. These types of system are called *moisture-limited fire regimes*, also known as *fuel limited* since there are too little plants available to burn as result of a lack of precipitation (Turco et al., 2017; Westerling & Bryant, 2007). A correlation between the burning of grasses and a period of abrupt precipitation, followed by a dry period is expected to be found (Rocca et al., 2014).

In contrast, California also contains relatively wet, densely forested ecosystems with abundant vegetation (fuel) present (Hurteau et al., 2014). The influence of one season with high precipitation is negligible. The precipitation will only help to make the plants and wood less flammable. Therefore, large fires can only occur when there is sufficient energy available to dry out the plentiful fuels, for instance a long hot arid summer (Rocca et al., 2014). A correlation between dry arid periods and the burning of wood is expected. These type of system are called *energy-limited fire regimes*, and are also known as *climate limited* (Turco et al., 2017; Westerling & Bryant, 2007). The lack of high temperature or energy and too much precipitation will limit the number of acres burned by wildfires (Thompson & Spies, 2009).

These systems are most common in north California and consist of mostly woodland and timber (Turco et al., 2017).

In this thesis, Mariposa County will be examined specifically, since its vegetation consists of lower montane forests. This type of vegetation is a combination of *moisture-limited fire regimes* and *energy-limited fire regimes*. This can be expected since Mariposa County is located in the center of California. The lower montane ecosystems have the optimal combination of fuel production and fuel drying. Therefore, fire frequency and severity are highest in this lower montane ecosystem (see Figure 2) (Rocca et al., 2014). The high fire frequency made Mariposa County an excellent region to research, since a lot of wildfire data was available.

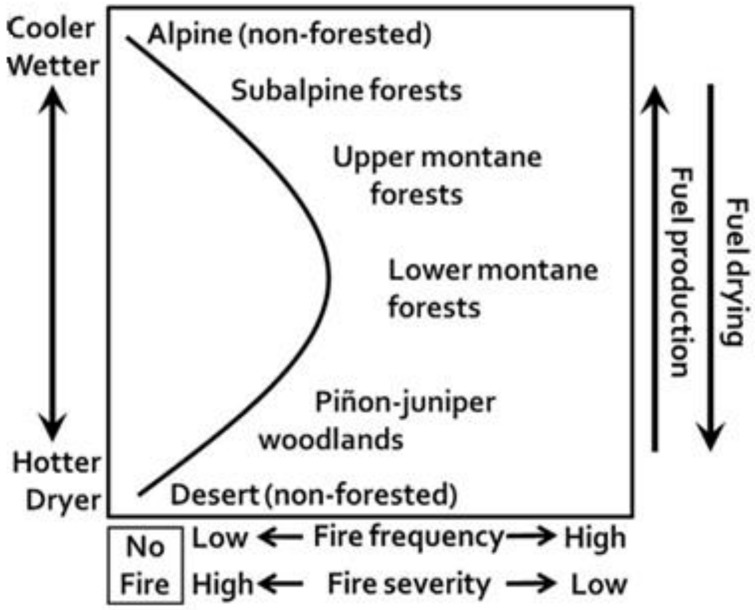

Figure 2 Generalized fire regimes defined by frequency and severity (curved line) across climatic gradients. Fuel production and fuel drying are also shown in relation to the climatic axis, this shows that fire regimes in drier and warmer ecosystems are typically 'fuel limited', while fires in cooler and wetter ecosystems are 'climate limited' (Rocca et al., 2014)

Since climate change has resulted in higher temperatures in California, an increase in *energy-limited fire regimes* is expected to be found in the north of California (Hurteau et al., 2014; Westerling & Bryant, 2007). This increase in temperature due to climate change is predicted to continue in the future. Therefore, it is expected that the amount of area burned will only increase in the coming years in North California (Westerling et al., 2011).
In the south of California, the increase in heat is only a predictor for more wildfires in *moisture-limited fire regimes* if this is accompanied by an increase in precipitation previous to

the high temperatures. Otherwise, a dry period caused by climate change will only stem the growth of fine-fuels and therefore decrease the number of acres burned. Changes in precipitation under climate change are less certain (Cayan, Maurer, Dettinger, Tyree, & Hayhoe, 2007). Therefore, it is not clear how the number of acres burned in South of California will react to this change in climate. Based on this, this thesis will not predict how the number of acres burned will react to changes in precipitation due to climate change.

1.3 Scope, goal, research question and hypotheses

Large fire frequency and economical damage in California have been researched before (Westerling et al., 2006), yet a possible increase in the number of acres burned in total per year is not clear. The number of acres burned does not solely include large fires, it also takes into account a possible cumulation of a large number of small fires that could have raged in one year. Therefore, the number of acres burned will reflect the economical damage and properties lost better. This essay will not solely examine the number of acres burned in California but will also look more closely at the number of acres burned in Mariposa County and type of vegetation burned.

To limit the scope, direct human intervention, wind conditions and available fuel will not be analyzed in this research.

The goal of this thesis is to determine the relationship between climate change and number of acres burned or type of vegetation burned in Mariposa County. If this relation can be determined, large wildfire outbursts and a future increase of wildfires due to climate change could be predicted better. If fire departments and residents are prepared to potential wildfire danger, human lives and properties can be protected better. Based on this goal and the theoretical framework presented, the research question is:

"How are the number of acres burned by wildfires and type of vegetation burned connected to climate change in Mariposa County?".

The following four sub questions will help to answer the research question:

1. How has the number of acres burned in California and Mariposa County changed over time?
2. How has climate change influenced the Mariposa County weather?
3. How does the Mariposa County weather influence the area burned?

4. How does the Mariposa County weather influence the type of vegetation being burned?

These sub questions will be discussed in the same order in the statistical analyzes in the methods section, the results section and the discussion. Combined, the results of these sub questions will lead to an answer to the main research question.

The increase in temperature caused by climate change will result in more acres and vegetation burned in *energy-limited fire regimes*. The influence of climate change on precipitation is less clear, therefore the influence of climate change on *moisture-limited fire regimes* is less certain. Since Mariposa County has both regimes and already has the highest fire frequency, changes in weather could result in less wildfires. But, as literature has shown that wildfire frequency has increased in California, it is expected to establish an increase in wildfire acres burned in Mariposa County as well. Resulting from the theoretical framework presented here, the hypothesis will be; **Mariposa County will show an increase in acres burned caused by wildfires due to higher temperatures caused by climate change.**

In the next chapters, materials, databases and relevant variables will be discussed in the materials section. Then a description of the used statistical analyses and methods will be given. This will be followed by the results and an explanation of the most important correlations found. Any limitations in this research will be discussed afterwards and this thesis will finish with a conclusion and recommendations for future research.

2 Data and methods

2.1 Data

2.1.1 California data

The wildfire data has been extracted from the California Fire Department (CalFire). CalFire keeps record of Historical Wildfire Activity Statistics (Redbooks). CalFire only keeps track of fires in the State Responsibility Area (SRA). This is the area where the State of California is financially responsible for the prevention and suppression of wildfires. The SRA does not include lands within incorporated city boundaries or in federal ownership. The State Responsibility Area is shown in Figure 3. This area has not changed significantly over time (<10%).

The California data has been used to create a complete image of the wildfire development over time, concerning acres burned and number of fires. The California wildfire data helps to put this change in fire frequency in perspective to the Mariposa County data. This comparison will show if the Mariposa county data reflects the same trends as the entire state.

CalFire provided a table with all the necessary data needed for the California wildfire analyzes (CalFire). This included number of fires (CAL_N) and number of acres burned (CAL_TOTAL) over a time period of 1933 to 2015 (see Table 1).

Figure 3 Wildfire Protection State Responsibility Area California - CalFire (2016).

2.1.2 Mariposa county data

In this thesis, the data analyses will focus on wildfire activity in Mariposa County. Large wildfires are rare events, therefore the analyzed area had to be of a certain minimum size (Westerling & Bryant, 2007). A city area would not have been large enough, since the frequency of wildfires would have been too low. Mariposa County has a medium to very high wildfire severity since it has lower montane ecosystems which are relatively very flammable ecosystems as discussed before (Rocca et al., 2014). This means Mariposa County has frequent enough wildfires that can be analyzed (see Figure 4).

Since the vegetation burned will be examined in this thesis, the area could not be too big either. CalFire holds records of vegetation burned per county. Therefore, the decision was made to examine a county. Mariposa County has a large SRA area which means there is plenty of data available about this county. This county has no big cities and the population density is low with 17 people per mi^2 (Statistical Atlas). Therefore, the vegetation has not been influenced by humans as much as the counties lying more westwards on the coast of California. Not as many build areas have influenced the burned area as Mariposa County owns a lot of protected parks (among them Yosemite National Park). The nature has been protected better over time in comparison to other counties. Therefore, Mariposa County will be less influenced by its land-use history.

Mariposa County Wildfire Data

CalFire protects, together with a few other agencies, a total of 443,800 acres in Mariposa County (CalFire). In Figure 4 the yellow, orange and red colored areas are SRA. This figure also shows the level of fire hazard severity. Yellow is *moderate*, orange is *high*, and red is *very high*. As shown in this figure, only the south-west part of Mariposa County has been analyzed since this is the part CalFire has registered data of. This area has not changed significantly over time (<10%).

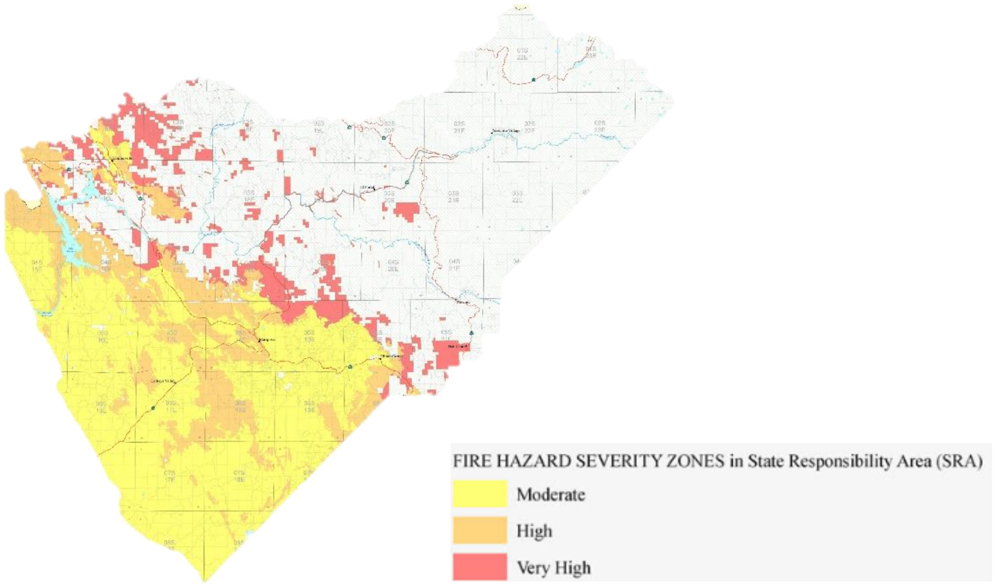

Figure 4 SRA Fire Hazard Zones Mariposa County - CalFire (2007). Most of Mariposa County SRA is categorized as moderate to high fire severity.

Mariposa County wildfire data from the CalFire Redbooks has been used. These Redbooks were manually scanned for the necessary data. A period of 1943 till 2016 has been analyzed. These Redbooks hold record of total Mariposa County acres burned (TOTAL), and Mariposa County vegetation type acres burned per year. The vegetation type categories CalFire used are acres grassland burned (GRASS), brushland burned (BRUSH), woodlands burned (WOOD), timber burned (TIMB), and other type of land burned (OTHER) (See Table 1).

This Mariposa County data has been used to determine a change in type of vegetation burned over time. As described in the introduction, the Mariposa County data is expected to show signs of both *energy-limited fire regimes* as well as *moisture-limited fire regimes.* An increase in timber and woodland being burned could imply the effect of an increase in temperature due to climate change (*energy-limited)*. An increase in grass and brushland being burned could be the result of alternate more wet and arid periods caused by changes in weather patterns due to climate change (*moisture-limited)*.

Mariposa County Weather Data

Mariposa County weather data is retrieved from Cal Adapt (Livneh et al., 2015). This is a dataset of gridded observed data. This dataset is used to receive information about the yearly average precipitation (mm/day) (PREC), minimum temperature (Celsius) (TMIN) and maximum temperature (Celsius) (TMAX) in the Mariposa County (see Table 1) (Livneh et al., 2015). The dataset is gridded to a 1/16° (6 km) resolution for the 1950–2013 period in California. Of the 247 grids expected to show measurements of precipitation, maximum and minimum temperature, merely 126 did have data. The Mariposa County weather data will show if there has been a significant change of weather of time (63 years) and if this could be a response to global climate change. This data is also used to find a correlation between weather patterns and wildfires (area burned, and type of vegetation burned).

Table 1 Variables used in this thesis.

California data	
Independent variable	
TIME	*Year corresponding to data (year)*
Dependent variable	
CAL_TOTAL	*Area Burned (acres, 1933 to 2015)*
CAL_N	*Number of wildfires (n, 1933 to 2015)*
Mariposa County data	
Independent variable	
TIME	*Year corresponding to data (year)*
TMIN	*Minimum daily weather, annual mean (degrees Celsius, 1950 to 2013)*
TMAX	*Maximum daily weather, annual mean (degrees Celsius, 1950 to 2013)*
PREC	*Daily precipitation, annual mean (mm/day, 1950 to 2013)*
Dependent variable	
TOTAL	*Area burned total (acres, 1943 to 2016)*
BRUSH	*Brushland area burned (acres, 1943 to 2016)*
GRASS	*Grass area burned (acres, 1943 to 2016)*
TIMB	*Timber area burned (acres, 1943 to 2016)*
WOOD	*Woodland area burned (acres, 1943 to 2016)*
OTHER	*Other type of land area burned (acres, 1943 to 2016)*

2.2 Methods and Statistical Analyses

The raw data extracted from the CalFire and Cal Adapt databases was first processed in Excel. Per year, per variable (TMIN, TMAX and PREC), a total of 126 measuring points was gained by this Cal Adapt data. In Excel an average of these 126 points was taken per variable, to have one average variable per year for each of the Mariposa County weather variables. It is assumed that Mariposa County has uniform weather.

The transformed data was loaded into SPSS Statistics 24. This program has been used to find means and standard deviations of the variables presented in Table 1. The Pearson Correlation test has been used to find all the necessary correlations between variables. This test is the strongest statistical test to find correlations between non-normally distributed variables.

To answer the four sub questions introduced in the introduction, four hypotheses were tested:

First, graphs were made of California wildfire frequency (CAL_N) and the California and Mariposa county area burned (CAL_TOTAL and TOTAL) over time (TIME). This was helpful to determine the overall expected trends in the variables. Then a Pearson correlation between TIME and CAL_N, CAL_TOTAL and TOTAL was performed. This answered the first sub research question and hypothesis: "California wildfire frequency and California and Mariposa County area burned, increased over time."

Second, the influence of climate change on Mariposa weather data had to be analyzed. If weather data showed a significant change in time, this could be caused by climate change. Pearson correlation between TIME and weather data TMAX, TMIN, PREC were performed. The second hypothesis is: "Mariposa County weather patterns changed over time."

To answer the third sub question, changes in vegetation type burned were analyzed using scatterplots and linearity. Type of vegetation burned variables (TOTAL, TIMB, WOOD, BRUSH, GRASS, OTHER) will be plotted over time (TIME) and Pearson correlations were performed. The third hypothesis is: "The type of vegetation burned in Mariposa County changed over time."

To answer the fourth sub question, correlations between Mariposa County weather data (TMAX, TMIN, PREC) and number of acres burned (TOTAL), and type of vegetation burned variables (TIMB, WOOD, BRUSH, GRASS, OTHER) were analyzed. The hypothesis is: "There is a correlation between Mariposa County weather data and number of acres burned or type of vegetation burned."

Last, to answer the main research question, a correlation between weather data changing over time and area or type of vegetation type burned should be found. Since this is the sole way this thesis could prove a correlation between area or vegetation type burned and climate change, using the data available. This will result in acceptance or a rejection of the hypothesis: the increase in temperature caused by climate change will result in more acres and vegetation being burned by wildfires in Mariposa County.

3 Results

3.1 Wildfire frequency and number of acres burned

To initiate the result analyses, the expected growth of wildfires since the mid 1980's must be found in the data. An increase number of wildfires per year is expected be found since this is the fire frequency. Surprisingly, the increase in wildfire frequency or number of wildfires is not evident in the data (see Figure 5). Since 1980, the data even shows a decline in the number of wildfires in California over time. This could be caused since this data includes all the wildfires per year instead of solely the number of large wildfires (>5000 hectares) (Barbero, Abatzoglou, Larkin, Kolden, & Stocks, 2015). The number of wildfires arising per year has been declining since the mid-1980's as shown in Figure 5, but it is still possible that an increase of large wildfires also happened in that same time period. This cannot be established in this data, since the size of these wildfires in California was not available.

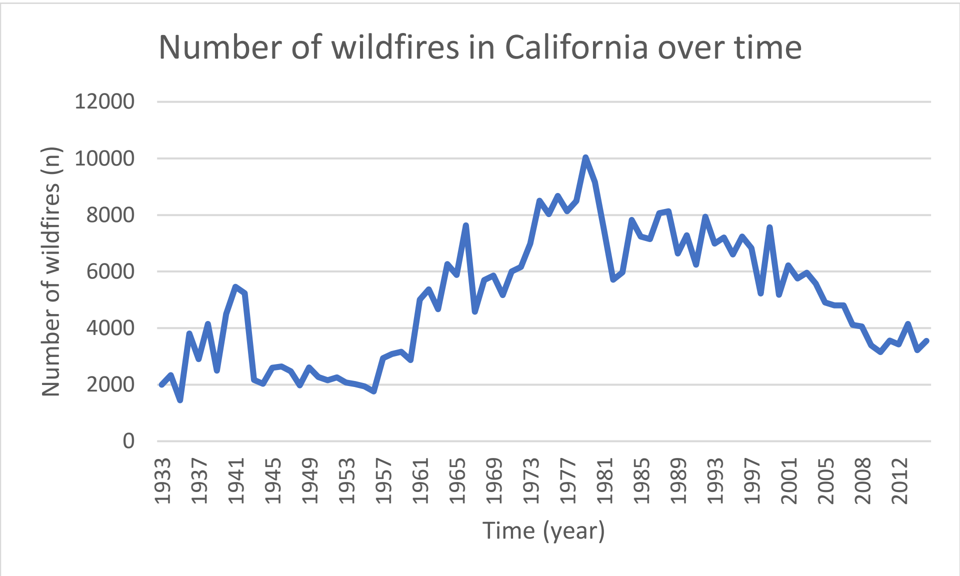

Figure 5 Yearly average wildfire number in California from 1933 to 2016.

The increase in California wildfire acres burned is not as evident as well, see Figure 6. There is a visible decline in acres burned around the 1940's, which could be the result of a successful fire policy in the beginning of the century as mentioned in the introduction (Busenberg, 2004). The expected increase in acres burned in California since the mid-1980's is less clear.

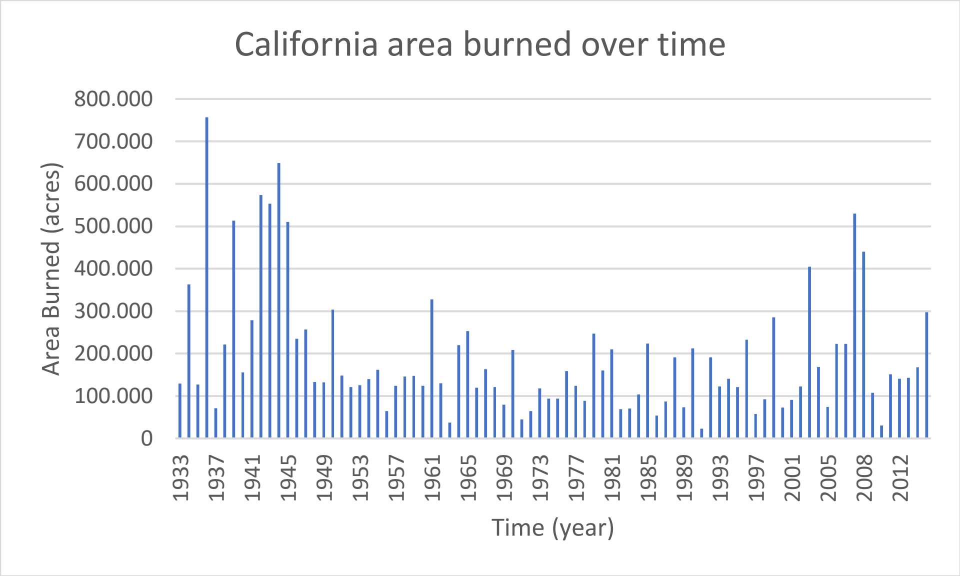

Figure 6 Total Area Burned in California per year from 1933 to 2016.

To remove the influence of years with a small area burned, 9-year moving averages have been taken to filter out the noise. Since the 1980's at least every 4 years 150.000 acres had been burned per year. Taking 9-year moving averages, small fires influence can be reduced. The result can be found in Figure 7. In this graph the increase in area burned over time since the mid 1980's is clearer. The 9-year moving averages of California area burned (from 1972 to 2016) and time has a significant ($p < 0.01$) Pearson Correlation of 0.829 (Figure 18 in the Appendix). Also, the dip in number of wildfire area burned is still visible, but has been shifted to the 1950's.

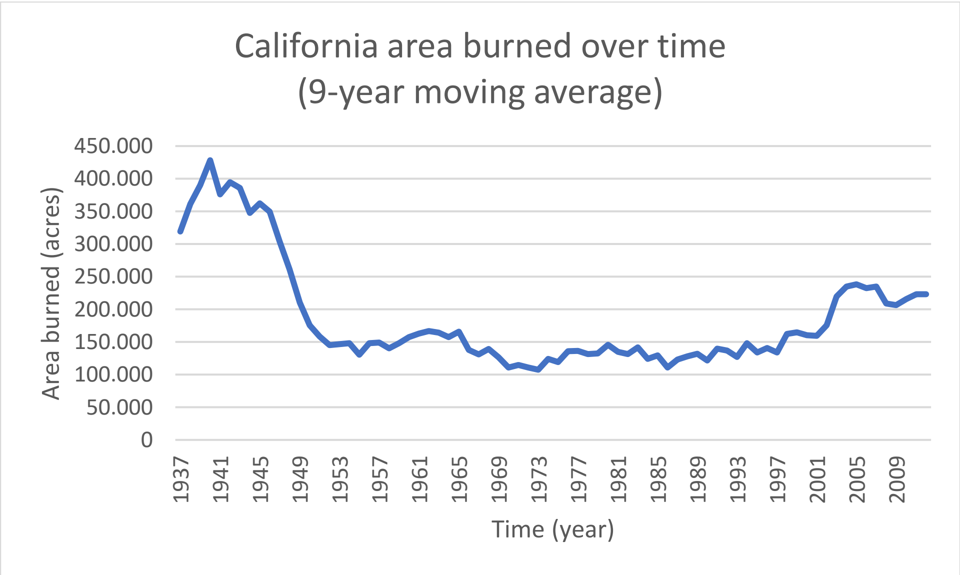

Figure 7 9-year moving average of area burned in California from 1933 to 2016. The corresponding year to the area burned shown is the median year.

Since the increase in burned acres over time is significant, the California data can be compared to the Mariposa county wildfire data (see Figure 8). This will show if the Mariposa County wildfire data is representative for wildfire trends in California. As can be established from the 9-year moving averages in Figure 9, the Mariposa County burned area has the same drop in area burned at the left side of the graph, only roughly ten years later. Around the mid-1980's, there is a cease in the decline of the 9-year moving averages acres burned per year, the same as can be found in the California graph. Since the 1980's an increasing number of acres are burned every year in Mariposa County. The 9-year moving averages of Mariposa area burned (from 1972 to 2017) and time have a significant ($p < 0.01$) Pearson Correlation of 0.842 (see Figure 19Figure 19 in the Appendix). Therefore, an increase in both California as well as Mariposa County area burned is visible. It is concluded that Mariposa County shows the same trend in increase of wildfire intensity as expected from literature (Turco et al., 2017; Westerling et al., 2006).

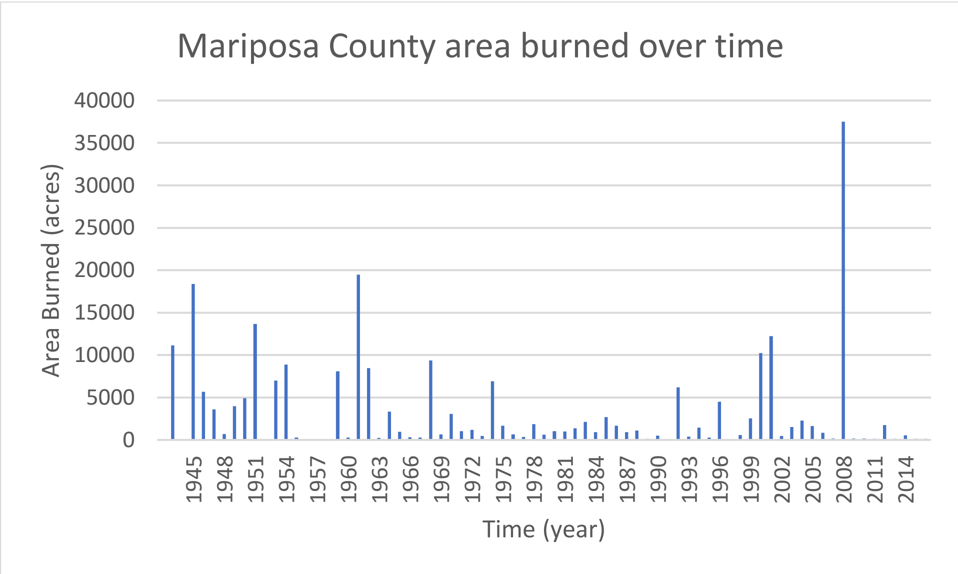

Figure 8 Total burned area in Mariposa County from 1943 to 2016.

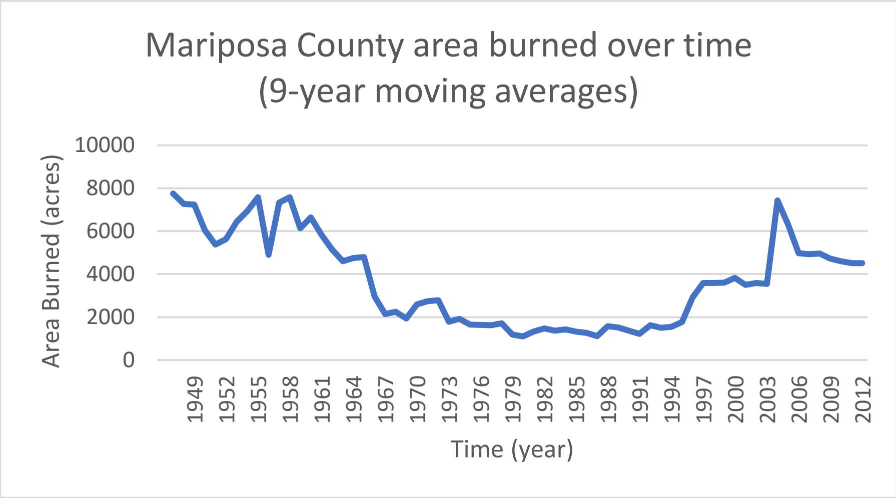

Figure 9 9-year moving averages of burned area in Mariposa County from 1943 to 2016. The corresponding year to the area burned shown is the median year.

3.2 Climate change effects in weather data

Climate change influences weather patterns and therefore researching weather changes over time is the best way to analyze the influence of climate change on Mariposa County. Changes in daily average temperature over time are expected, specifically as a result of a warmer surface of the earth (Kelly & Goulden, 2008). A significant increase ($p < 0.01$) in the annual average of daily minimum temperature has been found (Pearson correlation MIN and TIME, $r = 0.807$). The minimum temperature has increased since 1950 to 2013 with over 1,5 degrees Celsius as shown in Figure 10 (average minimum temperature 1950-1959: 3,1 degrees Celsius, average minimum temperature 2004-2013: 4,8 degrees Celsius). However, annual average of daily maximum temperature did not show a significant change over time as was expected (see appendix Figure 20). It was expected that precipitation would not show a clear change in time as discussed in the introduction, yet other research found the precipitation variability to increase as result of climate change (Kelly & Goulden, 2008). A change in precipitation in Mariposa County is not clear (see Appendix Figure 21). There is solely a correlation between Mariposa County weather data and time in case of minimum temperature found in this data.

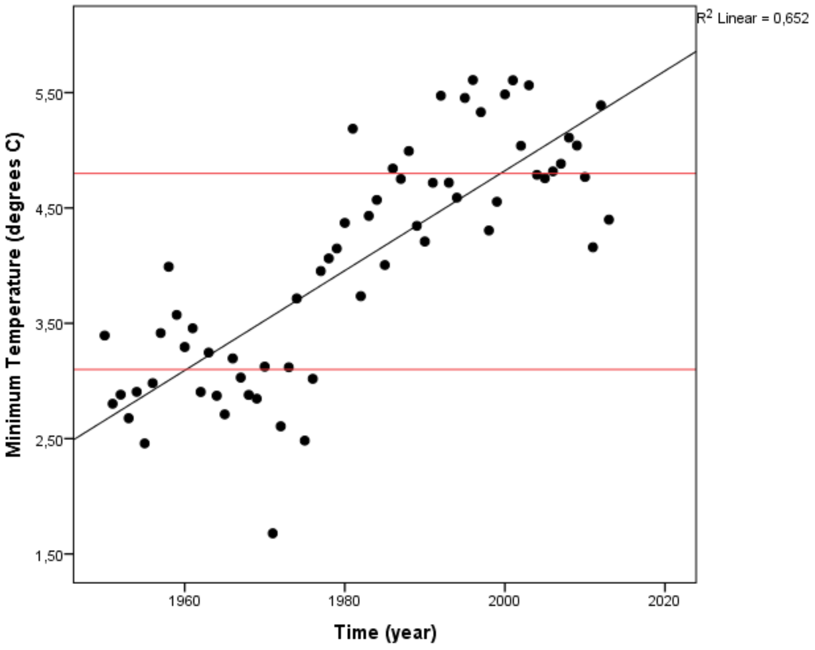

Figure 10 Each point represents a year in Mariposa County vs the average yearly minimum temperature for that year in Mariposa County for the 1950 – 2013 period. The red lines show the average minimum temperature in 1950-1959 (bottom) and 2004-2013 (top).

3.3 Weather and number of acres burned

Wildfires risks tend to be associated with relatively high temperatures in summers (Westerling & Bryant, 2007), and the general drying trend due to rising temperatures influenced by climate change (Hurteau et al., 2014). Since seasonally maximum temperature data was unavailable, annual maximum temperature data has been analyzed. Figure 11 shows that years with a high number of acres burned (more than 5,000 acres) are years with a temperature of at least 19,4 degrees Celsius. So not only seasonally, but also the annual average of daily maximum temperature seems to be an influence in the occurrence of large areas being burned.

As discussed before, Mariposa county lays in the middle of central California and is therefore expected to show signs of both *moisture-limited fire regimes* as well as *energy-limited fire regimes*. That means too little precipitation will have a negative influence on fuel availability in *moisture-limited fire regimes*, while too much precipitation will have a negative influence on the flammability of *energy-limited fire regimes*. This influence of both regimes can be found in Figure 12. All years with a high number of acres burned have had medium amounts of rain, between 1.2 and 2.7 mm/day. This weather-wildfire correlation is only present in years with a high number of acres burned and is therefore solely a condition of large areas being burned per year, but not a predicting variable. There is no significant correlation found between weather and number of acres burned (see Table 2 in the Appendix).

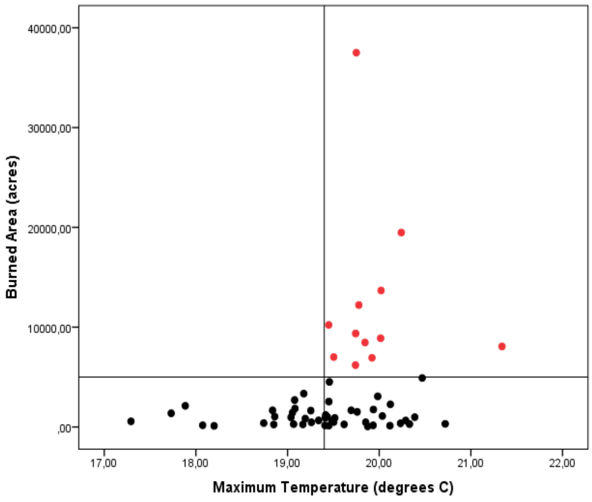

Figure 11 Each point represents the total area burned in Mariposa County in one year vs the average yearly maximum temperature for that year in Mariposa County for the 1950 – 2013 period. The red dots are years with a high number of acres burned (more than 5.000 acres). All these years had a higher maximum temperature than 19,4 degrees Celsius.

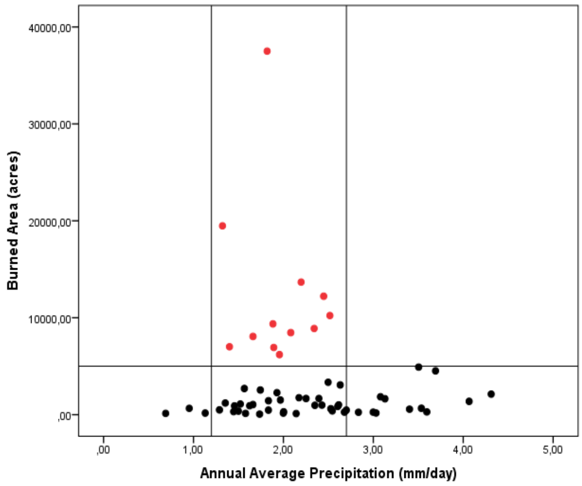

Figure 12 Each point represents the annual average daily precipitation in Mariposa County in one year vs the yearly total area burned for that year in Mariposa County for the 1950 – 2013 period. The red dots are years with a high number of acres burned (more than 5.000 acres). All these years had an annual average precipitation between 1.2 and 2.7 mm/day.

3.4 Type of vegetation burned and weather

As can be found in Figure 13, more than 50% of the vegetation area burned is grass from 1943 to 2016. Brushland is accountable for less than 40% and woodland and timber are both less than 5%. This could be expected, as explained in the introduction, since grass is the most flammable fuel, then brush, woodland and timber (Westerling & Bryant, 2007).

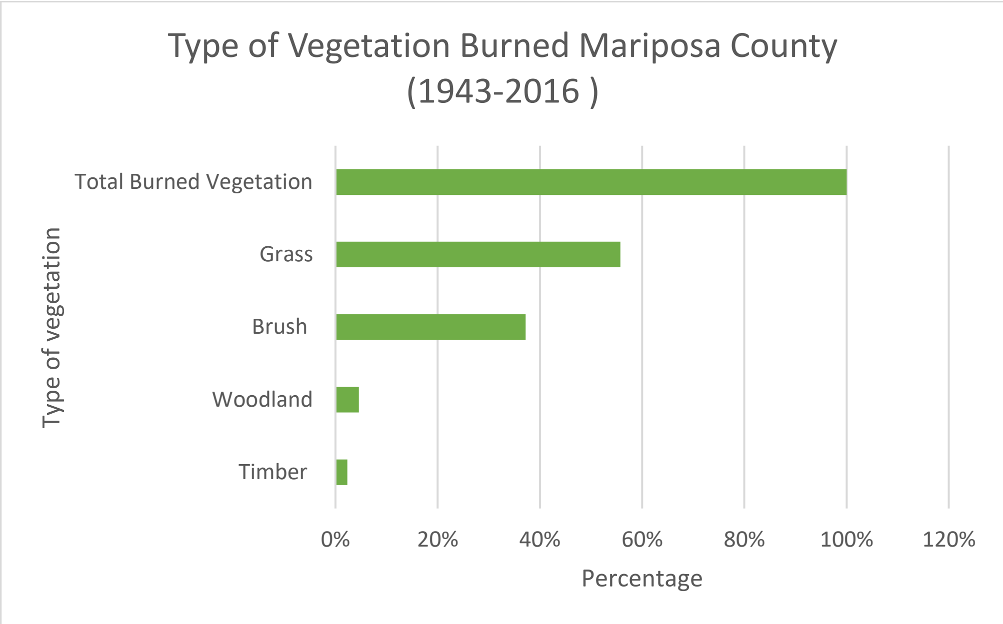

Figure 13 Type of vegetation area burned in Mariposa County in percentages from 1943 to 2016.

The 9-year moving averages of brush area burned and grass area burned is in Figure 14 shown. In Figure 15, the 9-year moving average of woodland is shown. Brush and grass burned area both show the decrease of area burned from the mid 1940's to the 1980's. Interesting is that woodland does not show this dip. This means that woodland burned very little before the 1980's and has not been influenced by a successful fire prevention protocol as is found in case of total, brush and grass burned area before the 1980's. In Figure 16, the linear increase of woodland area burned over time with a significant ($p < 0.01$) Pearson correlation (r) of 0.876 can be found.

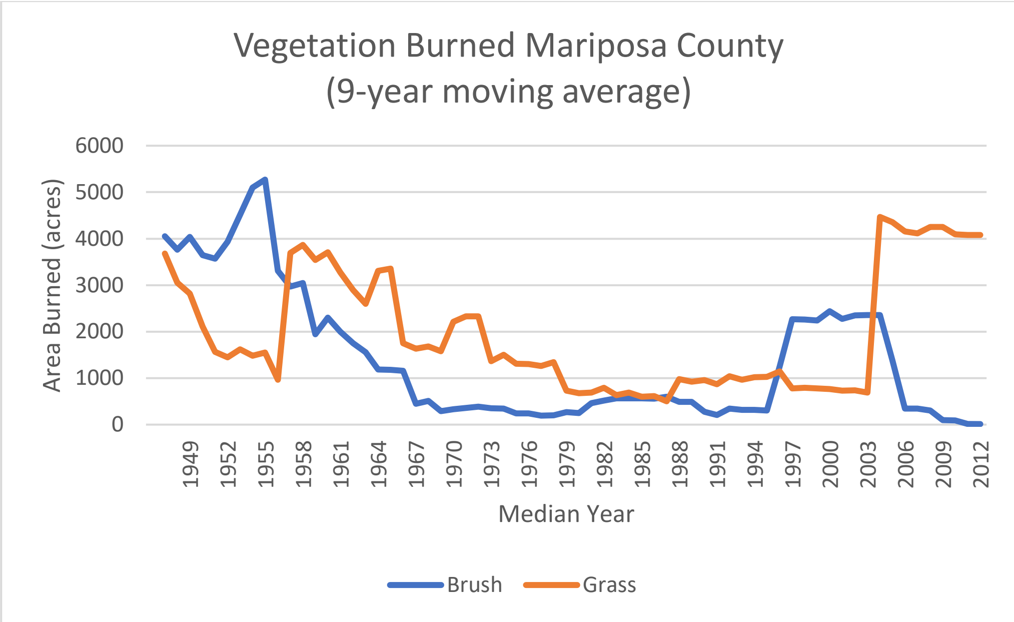

Figure 14 9-year moving averages of brush and grass area burned in Mariposa County from 1943 to 2016. The corresponding year to the area burned shown is the median year.

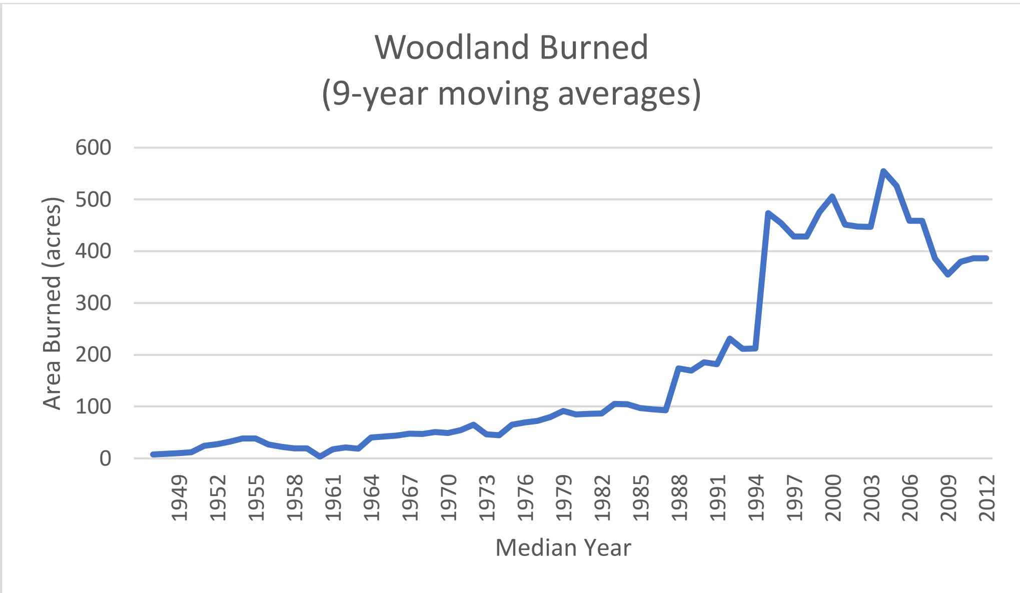

Figure 15 9-year moving averages of woodland area burned in Mariposa County from 1943 to 2016. The corresponding year to the area burned shown is the median year.

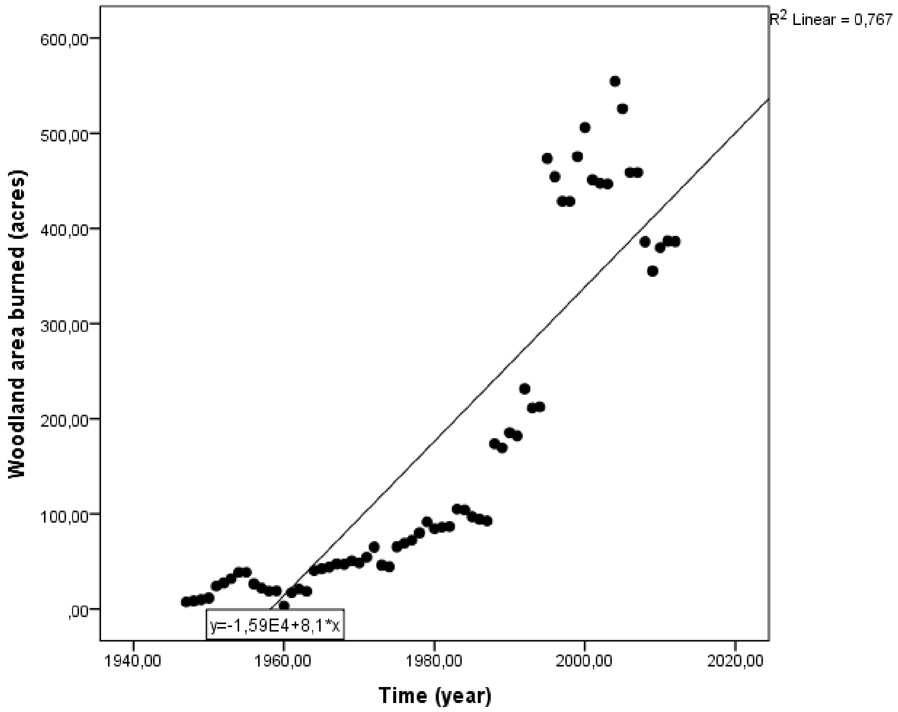

Figure 16 Each point represents the total woodland 9-year moving average area burned in Mariposa County in one from 1943 to 2016. The corresponding year to the area burned shown is the median year. A significant ($p < 0.01$) Pearson correlation (r) has been found of 0.876.

When the minimum and maximum temperature are high, more vegetation is expected to burn in e*nergy-limited fire regimes*. This is caused by more energy being necessary to burn the less inflammable fuels, as has been explained in the introduction. The data shows no direct significant correlation between high minimum temperature or maximum temperature and vegetation burned (see Pearson Correlation table in Appendix, table 1). But in case of increase over multiple years; minimum temperature has a strong Pearson correlation ($p < 0.01$) of 0.829 with the 9-year moving averages of woodland area burned.

When a period of a lot of precipitation is followed by a dry period, more grass and shrublands are expected to burn. These *moisture-limited fire regimes* are explained before. The data shows no significant correlation between high minimum temperatures, high maximum temperatures, high levels of precipitation and grass or bushland burned (see Pearson Correlation table in Appendix, Table 2).

Overall, only a significant correlation between minimum temperature and 9-year moving average of woodland has been found. Therefore, there is a single correlation found between Mariposa County weather data and type of vegetation burned in this thesis's data.

4 Discussion

4.1 Results summary

To answer the research question: “How are the number of acres burned by wildfires and type of vegetation burned connected to climate change in Mariposa County?”, the results will be discussed in this section. The sub questions will be answered in the same order as discussed in the introduction and results. Combined they will answer the main research question.

To answer the first sub question: “How has the number of acres burned in California and Mariposa County changed over time?”, results show that fire frequency has not increased in California, in contrast to what was expected. This could be the result of using data that included all fires started, not solely large fire (>5000 hectares). After using 9-year moving averages of area burned in California and Mariposa County, an increase in area burned since the 1980’s can be found. This could be the result of climate change, but no correlation between increase of area burned and weather has been found.

The second sub question is: “How has climate change influenced the Mariposa County weather?”. The influence of climate change on the Mariposa County weather could only been found in the data in a higher minimum temperature in the Mariposa County weather. The minimum temperature has significantly increased over time (1950-2013) with more than 1,5 degrees Celsius, this could be caused by climate change.

The third sub question is: “How does the Mariposa County weather influence the area burned?”. No significant correlation between weather and area burned could be found. Years with high temperatures did not necessarily result in more wildfires. Yet, a minimum temperature of 19.4 degrees Celsius was found for years with a large area burned (>5000 hectares). Years with a large area burned (>hectares acres) showed a very average precipitation. Too much rain will negatively influence the flammability of the vegetation and too little rain will result in too little grass and brush vegetation (fine-fuels) available.

The fourth sub question is: “How does the Mariposa County weather influence the type of vegetation being burned?”. A correlation between changing weather and vegetation type burned should be found. A direct correlation is for example; years with high temperatures result in more timber or woodland burned and years with a lot of precipitation result in more brush and grass burned. Direct correlations between weather and type of vegetation burned were expected to be found but did not show in the Mariposa data. Nevertheless, an indirect correlation could be found; a correlation between minimum temperature and the 9-year moving averages of number of woodland acres burned. Both have been increasing linearly since the 1950's (see Figure 10 and Figure 15). Indirect correlations of 9-year moving averages between weather and the other types of vegetation (grass, brush and timber) do not show significant.

The answers to the sub questions will be combined to answer the main research question: "How are the number of acres burned by wildfires and type of vegetation burned connected to climate change in Mariposa County?". Since the mid 1980's, number of acres burned have been increasing in Mariposa County and California. Also, minimum temperatures in Mariposa County have been increasing since the 1950's. This is expected to be caused by climate change. An increase in 9-year moving averages of woodland burned (1943-2016) is significantly correlated to this increase in minimum temperature. Therefore, the increase in 9-year moving averages of woodland could possibly be caused by climate change. Causality has not been researched in this thesis, but this careful conclusion is based on the theoretical framework presented in the introduction and correlations found in the data.

4.2 Limitations

A change in climate would be expected to shift plant distribution as species expand in newly favorable areas and decline in hostile locations (Kelly & Goulden, 2008). Therefore, the increase in woodland burned could be a result of more woodland being available over time. Yet, this is not likely since researchers found that grassland expanded due to climate change, largely at the expense of woodland and brushland (Lenihan, J. M., Bachelet, D., Neilson, R. P., & Drapek, R., 2008). This could be an explanation for the increase found in grass and brush vegetation being burned. Yet, over time most of the state's forests have been logged. Native oak woodlands are in decline and native grasslands have almost completely disappeared according to Lenihan et al. (2003). This could influence the data since less vegetation is able to be burned. The change in vegetation in Mariposa county should be taken into account in further research.

To find a correlation between maximum temperature and climate change over time, a bigger area could have been analyzed. The minimum temperature showed a clear significant increase of over 1,5 degrees Celsius from 1950 to 2013. However, this increase was also expected to be found at the maximum temperature. Instead, a non-significant change was found over time in case of maximum temperature. Daily precipitation has stayed somewhat the same over time, which was expected as this variable reacts unpredictable to climate change (Cayan et al., 2007*;* Westerling & Bryant, 2007).

The Mariposa weather data was used for all the county, instead of solely the SRA weather data. This resulted in weather data that is not a perfect fit for the burned area analyzed. The Livneh et al. (2015) weather database was not complete. Some of the grids consistently missed data. Therefore, some Mariposa county coordinates are not taken into the average annual weather data calculated. Of the 247 grids expected to show measurements of precipitation, maximum and minimum temperature, merely 126 did have data. These missing data were not randomly distributed through the database. Clusters of a maximum total of 15 measuring points were missing. This means that areas up to of $15*36km^2 = 540\ km^2$ have no weather data in Mariposa County. This is a considerable part of the complete county, which has a surface of 3.789 km^2. The yearly weather data did not show a significant difference in different measuring grids in Mariposa County, so the influence of this limitation should not be overestimated.

To examine the influence of a wet period followed by an arid period on wildfires in *moisture-limited fire regimes,* monthly weather data would have been more useful. The influence of long dry and hot periods on wildfires in *energy-limited fire regimes* might have been clearer as well, since smaller time periods, like seasons, could have been chosen to analyze. Annual data is less clear, since a wet spring period, followed by an above average dry summer period results in an average precipitation mean per year. The time scales and timing give drought and wet periods their strongest influence (Turco et al., 2017).

Mariposa is a county in the middle of California with influences of both *moisture-limited fire regimes* as well as *energy-limited fire regimes.* Therefore, clearer correlation between the influence of weather on the regimes could have been established if a North and South California region had been chosen. If these two regions where to be compared, a more evident distinction between the two different weather circumstances that promote different plant burning could have been made. Mariposa is already a county with the highest fire risk due to its vegetation (Rocca et al., 2014). As can be seen in Figure 2 in the introduction, changes in weather caused by climate change could even result in a decrease in fire frequency.

The availability of burnable biomass was not taken into account in this thesis. The accumulation of fuel over time as result of fire prevention programs could not have been researched since there was no record available of the amount of fuel in Mariposa County. This could have a great influence on the scale and frequency of wildfires (Busenberg, 2004). The influence of periods without wildfires influence the risk of a future wildfire because of this accumulation of fuels. After a few years without a wildfire, the risk of a large wildfire increases. This has not been taken into account in this thesis.

The influence of winds is also not considered in this thesis. Winds have the capability to fan wildfires and provide them with oxygen (Fried, Torn, & Mills, 2004). Research has shown that wind speed has the most effect on fire-spread in grasslands (Cheney, Gould, & Catchpole, 1993). This variable could provide insight in the outbreak of large fires as well.

5 Conclusion and recommendation

As found in the results, climate change could be the cause of an increased minimum temperature in Mariposa County and an increase in woodland burned. The increase in other vegetation burned was not significant but could also be caused by climate change. This thesis only researched correlations, not causality. Yet, the careful conclusion that climate change could be the cause of an increase in minimum temperature and woodland burned, is based on the theoretical framework presented in the introduction and correlations found in the data. Therefore, to decrease wildfire frequency and intensity in California, as stated in the problem definition, climate change should be mitigated according to this thesis.

As previously discussed, a decrease in California wildfire area burned from 1930 to 1950 can be found in Figure 7. This is probably caused by successful wildfire prevention policies. Yet, Busenberg (2004) stated in his article, that the increase in wildfire area burned since the mid 1980's is caused by that same wildfire policy (Westerling et al., 2006). Fuel accumulation due to the lack of small fires has greatly increased the risk of damaging, high-intensity wildfires in California. Therefore, the importance of fuel-control cannot be underestimated. The restauration of native, more fire resilient vegetation will also prevent wildfires. Nevertheless, fuel-control and ecological restoration will not be enough to decrease the frequency of wildfires. These measures should be combined with a mitigation plan of climate change.

Recommended is that future research will look at the combination of fuel availability, winds, high temperatures, changes in vegetation and precipitation influence on increasing areas being burned by wildfires. The weather data must be monthly or daily, instead of annual, so trends of shorter dry and wet periods can be examined better.

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7 Expression of gratitude

A special thanks to my bachelor thesis mentor dr. Mara Baudena for the guidance. She was always available to answer my questions. A thanks to second reader Stefan Dekker. And a thanks to the members of my peers group who consulted me and gave me feedback.

8 Appendix

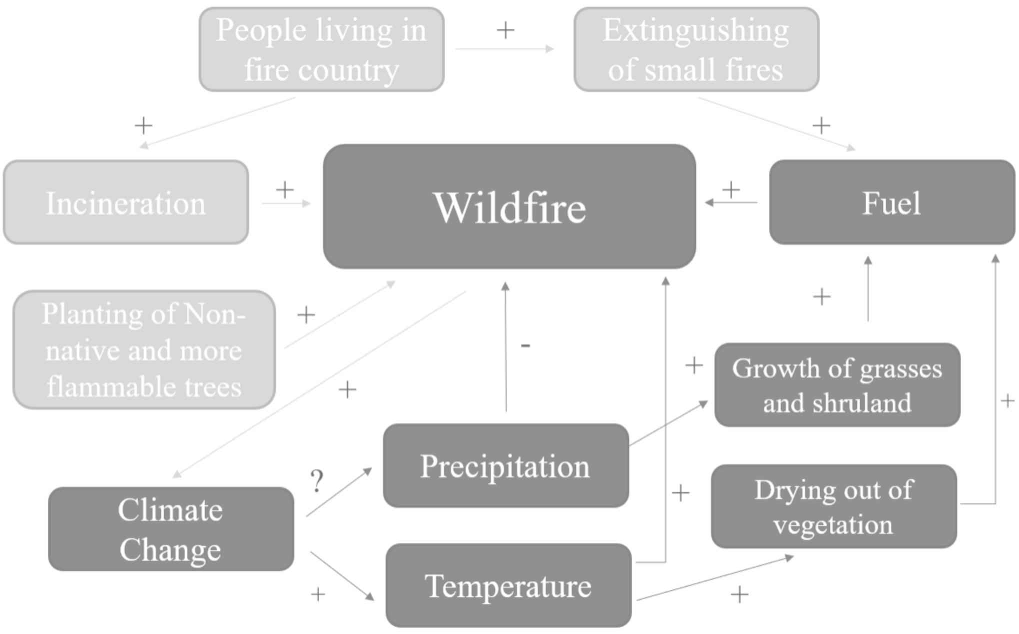

Figure 17 Wildfire feedback system. The dark grey boxes and arrows are the variables and their influence this thesis will focus on.

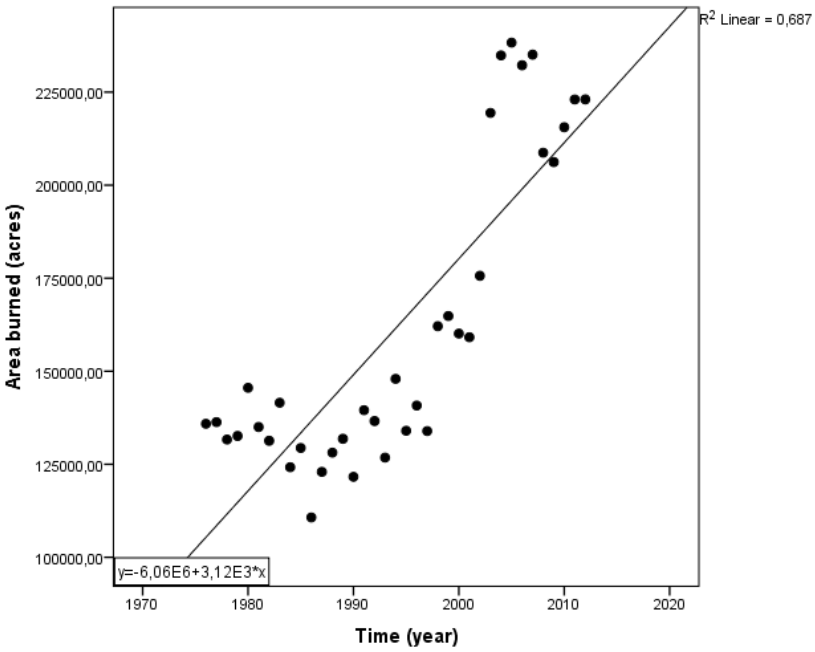

Figure 18 Each point represents a 9-year moving average of acres burned in California since 1972 to 2016. With the point shown at the median year. Acres burned changed over time with a significant ($p < 0.01$) Pearson correlation (r) of 0.829.

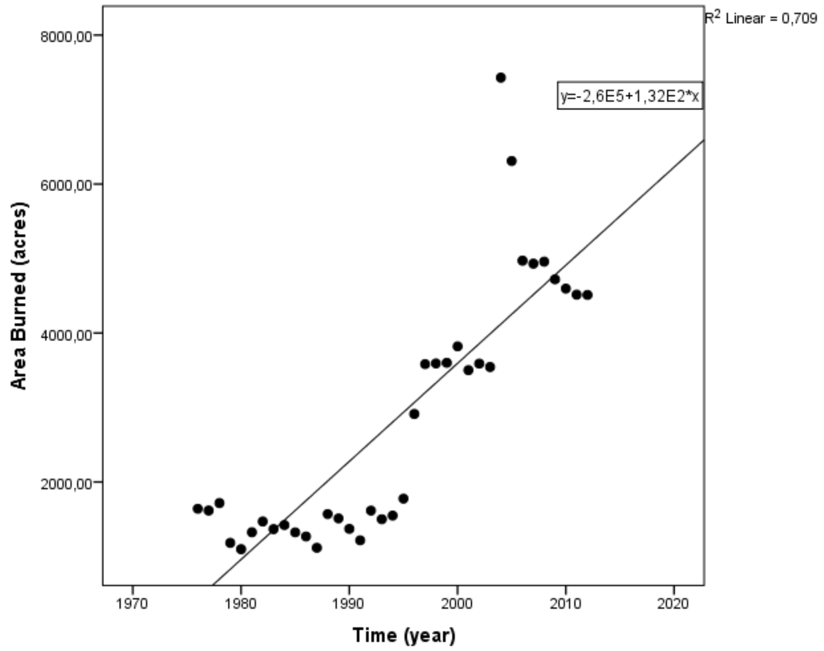

Figure 19 Each point represents a 9-year moving average of acres burned in Mariposa County since 1972 to 2016. With the point shown at the median year. Acres burned changed over time with a significant ($p < 0.01$) Pearson correlation (r) of 0.842.

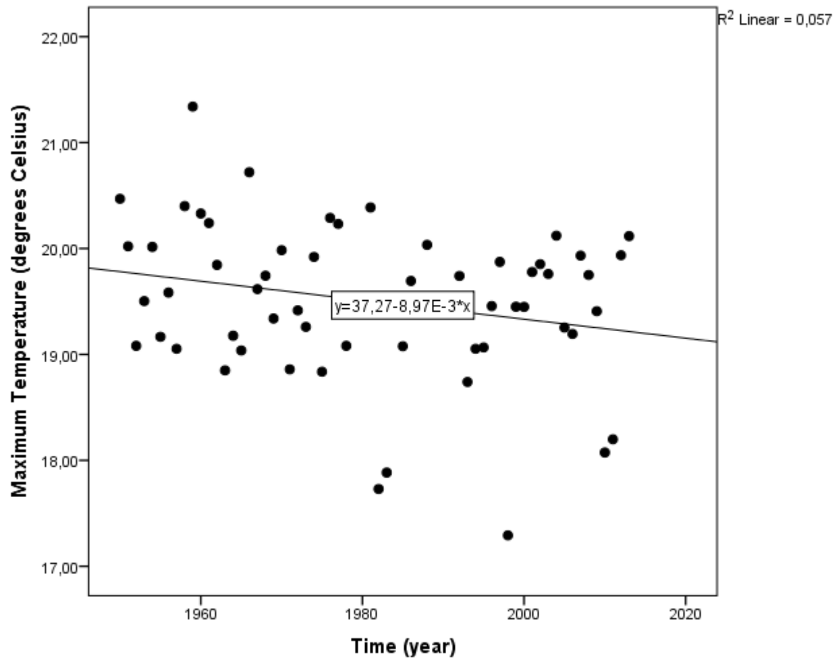

Figure 20 Each point represents a maximum temperature in degrees Celsius per year in Mariposa County from 1950 to 2013. No significant change in maximum temperature over time was found.

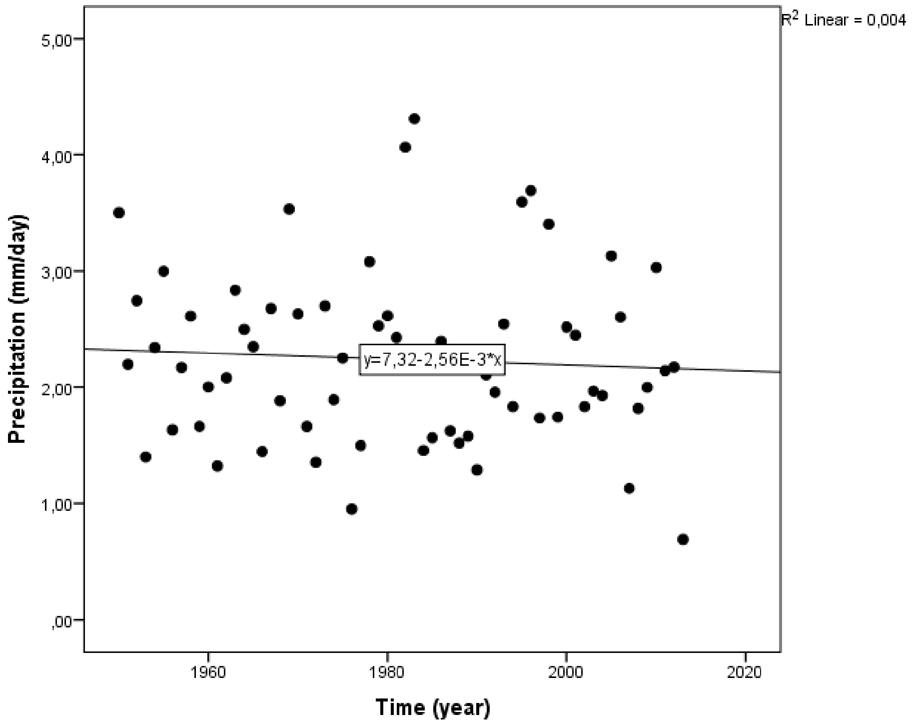

Figure 21 Each point represents an average annual precipitation in mm in Mariposa County from 1950 to 2013. No significant change in average annual precipitation over time was found.

Table 2 Means, standard deviations and Pearson Correlations with significance of Mariposa County variables.

	M	SD	1	2	3	4	5	6	7	8	9	10
1. Timber Area Burned	38,20	121,823	-	,058	-,026	,331*	,799**	-,080	,111	,250	,283	,189
2. Woodland Area Burned	233,46	551,629		-	,781**	,074	,073	-,033	,801**	,129	,240	-,076
3. Grass Area Burned	1568,07	5098,692			-	-,022	-,014	-,069	,939**	,111	,111	-,049
4. Brush Area Burned	701,26	1877,287				-	,029	-,098	,316*	,085	,254	,106
5. Cultivated Area Burned	1,67	7,648					-	-,057	,022	,129	,237	,272
6. Other Type Area Burned	5,78	22,518						-	-,093	-,193	,067	,008
7. Total Area Burned	2548,43	5837,227							-	,142	,208	-,011
8. Max Temperature	19,37	0,689								-	,200	-,624**
9. Min Temperature	4,45	0,892									-	,151
10. Daily Precipitation	2,21	0,803										-

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).