

California Wildfires

Team 7500: Gators

April 14, 2021

By: Anushka Srinivasan, Siona Tagare, and Reva Tagare

## **Acknowledgments**

We would first like to thank the Actuarial Foundation for this opportunity to participate in the 2021 Modeling the Future Challenge and for introducing us to actuarial science.

We are grateful to our families, peers, and teachers who encouraged us throughout this process.

We thank Ms. Laura Mitchell, our actuary mentor, for her wisdom and guidance. From cheering us on at every symposium session to offering feedback on all of our drafts, Ms. Mitchell's support was vital to our success.

Finally, we would like to extend our gratitude to our team coach and statistics teacher, Mr. Kyle Barriger, without whom this project would not have been possible. Mr. Barriger's unwavering support and commitment to this team were truly invaluable, and we are endlessly grateful to him for teaching us all that we know about statistics. We are honored to have learned from and worked with him over the last few months.

## Executive Summary

Over the past few years, California's fire seasons have grown in both frequency and severity: 15 of the state's 20 most destructive wildfires<sup>1</sup> have occurred within the last five years, destroying 19,000 structures (*Top 20 Most*, 2020, p. 1). This damage has taken a notable toll on our identified stakeholders: homeowners, government agencies, and insurance companies will be affected the most by wildfire damages. Homeowners sustain significant losses: they are not only hurt financially but also emotionally, as they lose all of the memories attached to their homes. The state government and insurance companies must cover the cost of destroyed infrastructure and public property, so they absorb significant financial risk. In 2018, the Camp Fire alone drained \$28.5 billion from the government and insurance companies (*Facts + Statistics*, 2020). Major fires such as the Camp Fire and the Woolsey Fire account for a majority of structural damage; in 2018, five major fires contributed to 98.3% of the structures destroyed (*Cal Fire*, n.d.). Since such few fires cause so much structural damage, we chose to focus on these few major fires to gain an accurate estimate of damage costs and recommend mitigation strategies.

We examined the increasing frequency and severity of wildfires in our mathematical models. First, we modeled the frequency of major fires over the years and determined that the number of major fires will increase rapidly over the next few years. We then determined that damage costs of fires rise at an increasing rate over time, and will soon reach an unsustainable level. Finally, we discovered that the number of structures damaged predicts damage costs and that structures destroyed and structures damaged are correlated, so we investigated how topography and duration affect how many structures are destroyed. Our models predict that the number of fires will increase from 13 in 2020 to 24 in 2025. The severity of these fires will increase as well: we predicted that the damage costs of these major fires will continue to increase, with the 2024-2025 fires costing \$19.7 billion.

We identified northern fall fires caused by electrical issues as the most destructive, as these fires account for over 50% of the structures destroyed by all major fires between 2008 and 2019. Furthermore, 65% of the major fires in our dataset occurred in Northern California, so we targeted our recommendations towards this region of the state. Thus, we focused on the northern fall electrical fires in our analysis of methods to prevent major fires in the future.

In order to mitigate these destructive electrical fires, we recommended a government-industry partnership between the California Public Utilities Commission (CPUC) and Northern California electrical companies to fund wildfire prevention efforts, including covered conductors and undergrounding. We also proposed increasing efforts to educate homeowners about fire safety when they buy insurance or purchase a home in order to mitigate fire damage. Additionally, we recommended launching a social media campaign to increase awareness about wildfire prevention and relief. In order to protect insurance agencies from risk, we proposed a risk pooling mechanism to ensure no single agency bears the brunt of a major fire's damages. Finally, throughout our project, we noticed the lack of credible and comprehensive data regarding major fires. Wildfire data lie with many different entities due to separate jurisdictions; however, these agencies must come together to compile their data in order to make more accurate predictions in the future. Currently, the most comprehensive data are from Cal Fire, but even these data have inconsistencies and lack specific information.

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<sup>1</sup> For the purpose of this project, we will use the terms "wildfire" and "fire" interchangeably.

## Introduction and Background

Across the state of California, the frequency and severity of wildfires drastically increases every year, costing the state billions of dollars in structural damages. In this project, we examine the property losses sustained by homeowners and the economic losses sustained by insurance companies and government agencies. We explore methods including infrastructure improvement, curriculum reform, and new insurance strategies to mitigate these losses.

Eight of California's ten largest fires occurred in the last decade, and 2020 has shattered all wildfire records, burning through over 4.2 million acres (*2020 Incident*, 2020). These fires cause extreme damage to infrastructure and housing, forcing residents out of their homes and requiring the government and insurance agencies to pay tremendous amounts of money for repairs. Effective mitigation strategies must be informed by the largest stakeholders: homeowners, insurance companies, and the state government. These stakeholders also have significant capacity for making change, so recommendations proposed to these groups would have the largest impact due to their direct involvement with wildfire mitigation.

As California fire seasons grow more intense, homeowners face serious risks to their property: Versik's 2019 Risk Analysis claimed that around two million homes in California were at high or extreme risk from wildfires – just under 15% of all homes in the state (*Facts + Statistics*, 2020). In fact, of the 20 most destructive fires in California, 15 have occurred within the last five years (*Top 20 Most*, 2020, p. 1), destroying over 19,000 structures. The destruction of and damage to properties have rendered homes uninhabitable, requiring mass evacuation and displacement. In 2020 alone, fires forced the evacuation of around 70,000 homeowners (Stelloh & Burke, 2020) and displaced an additional 53,000 (Wiggleworth, 2020). The result is great financial strain on these homeowners to find new housing, and on insurance agencies to fulfill claims. Insurance agencies and the state government are also known to be decimated financially as they pay billions of dollars to address the effects of the wildfires. The combined fire seasons of 2017 and 2018 cost insurance companies more than \$25 billion in damages (Fredschun, 2020). Furthermore, infrastructural damages such as the destruction of roads, collapse of electrical systems, and interference with transportation and communication networks place even more monetary responsibility on already overburdened local government agencies.

In exploring the long-term impacts and consequences of wildfires, data reveal that a single major wildfire can destroy an area's economy and the denizens' livelihoods for years to come. For example, in 2018, the town of Paradise, California was devastated by the catastrophic Camp Fire that claimed 85 lives. The blaze destroyed 95% of Paradise's buildings within six hours, costing the local and federal governments almost \$20 billion in damages (*Cal Fire*, n.d.). Over two years after the Camp Fire, Paradise is still struggling to rebuild and recover from the unprecedented wildfire damages (McKay, 2020). Not only must the citizens of this town replace hundreds of destroyed homes, they must also prepare for the reality of future fires being equally, if not more, destructive. The current rebuilding timeline is set for ten years, demonstrating just how much one major fire can change an entire community's existence. Paradise has now updated its fire mitigation plans, early warning systems and evacuation strategies, and fire safety courses for all residents. Beyond these plans, they have also prioritized debris and tree removal in hopes of reducing the risk of major spread and fire escalation (McKay, 2020).

Investigation of the damages of California fires reveals that a single major fire causes significantly more damage than hundreds of smaller wildfires. For example, in 2015, 96.8% of the destroyed structures in California were attributed to five fires that burned over 50,000 acres; however,

there were a total of 8,283 fires in 2015 (*Cal Fire*, n.d.). Similarly, in 2018, seven major fires damaged 98.6% of the destroyed structures; however, there were a total of 7,948 fires that year (*Cal Fire*, n.d.). Clearly, very few fires account for almost the entirety of structural damage and loss in California, so focusing on these major fires will yield accurate predictions of reimbursement and damage costs. Furthermore, tailoring recommendations and risk mitigation to the major fires would greatly diminish the number of structures lost to wildfires, and in turn support homeowners, insurance agencies, and the state and local governments in maintaining more year-to-year stability. For these reasons, we choose to focus solely on major fires in our project.

Thus far, studies on major wildfires have been severely limited by the lack of complete and relevant data regarding damage and costs. Since California wildfires are managed by several unique organizations (including California Department of Forestry and Fire Protection, the United States Forest Service, the Bureau of Land Management, local fire departments, and the National Park Service) (*Cal Fire*, n.d.), there are several gaps in knowledge regarding the damages of major wildfires in California over the last two decades. The location of a fire largely determines under which jurisdiction it falls, and the various organizations differ in the data they collect and present. California Department of Forestry and Fire Protection (Cal Fire) provides relatively comprehensive data regarding the damage costs by county and year; however, local fire organizations and the Bureau of Land Management provide little to no information. Therefore, most of the overall estimates for cost are only partial estimates, given the limits of available data.

## Data Methodology

Our data are from the California Department of Forestry and Fire Protection (Cal Fire), specifically the California Incident Data and Statistics Program (Cal Stats), and encompass fires in California from 1987 to 2020. Cal Fire tracks wildfires and other disasters within and around California. Since Cal Fire is one of the oldest wildfire agencies in California and is known to have the most comprehensive California wildfire statistics, their data are the best possible choice in our analysis of historical trends. Additionally, 76.4% of California's land is under Cal Fire's Direct Protection Area (DPA), so the agency is responsible for substantially more land than any fire protection organization in the state. Direct Protection Area, also known as Direct Protection Agency, is "the area for which a particular fire protection organization has the primary responsibility for attacking an uncontrolled fire and for directing the suppression action" (*Direct Protection*, n.d.).

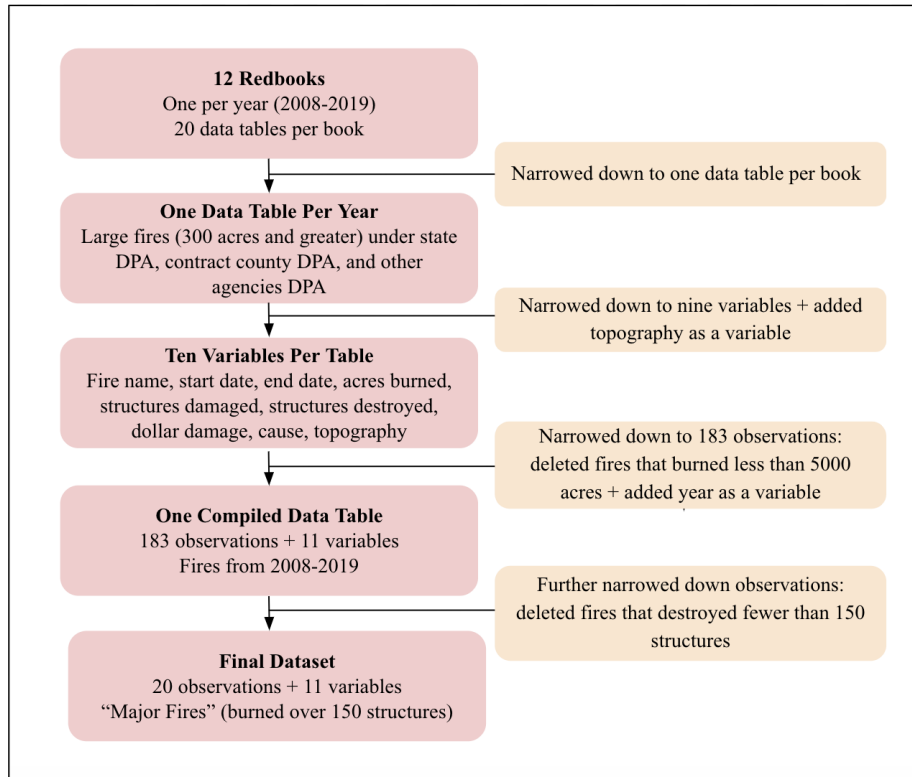
Cal Fire publishes annual Wildfire Activity Statistics reports, called redbooks, that provide a log of all wildfire incidents within the year that Cal Fire personnel and resources addressed (*Cal Fire*, n.d.). These redbooks are available for the years 2008-2019, and only include specific information (i.e. costs) for fires whose suppression and damage costs used California state funding (*Cal Fire*, n.d.). The redbooks' data support our analysis of historical trends by allowing us to generate a model of the number of wildfires over twelve years, creating an accurate representation of wildfire trends in California. These data can also be used to project future trends, as we can extrapolate from the historical data to estimate the number of fires in future years.

Because Cal Fire switched from one web-based reporting service to a different web-based reporting service in 2019, there may be discrepancies and missing values in the dataset, especially for earlier years (*Cal Fire*, n.d.). However, Cal Fire does provide the most comprehensive and accurate data on California wildfires, and these discrepancies are few and far between. Furthermore, Cal Fire is not the sole Direct Protection Agency; as mentioned above, California is divided into several jurisdictions, and many different agencies respond to the California wildfires (*Cal Fire*, n.d.). This wide range of agencies results in gaps in the data, as Cal Fire only reports the dollar damage<sup>2</sup> of fires that occur within its jurisdiction. Therefore, since Cal Fire only provides specific costs for fires under its own jurisdiction, fires under the jurisdiction of the Bureau of Land Management, local fire departments, the National Park Service, etc. do not have such specific dollar damage. Further research reveals that these other agencies provide far less data and information than Cal Fire, and thus dollar damage for the fires under other DPAs is unknown.

In order to obtain the dollar damage data and other critical information, we further explored the data from the redbooks. The following flowchart details the general process of our methods to clean and consolidate this data.

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<sup>2</sup> For the purpose of this project, we will use the terms "dollar damage" and "damage costs" interchangeably. Dollar damage is defined as "estimates of the total property and contents dollar loss in terms of replacement in like kind and quantity. This estimation of the dollar loss includes property and contents damaged by fire, smoke, water, and overhaul. This does not include suppression costs or indirect loss, such as business interruption" (*Cal Fire*, n.d.).



Each of the 12 redbooks contains around 20 data tables, so we had 240 data tables to sift through. Within a redbook, there are two categories relevant to our study: wildfire statistics from California Wildfire Agencies and wildfire damage from Cal Fire. The first category contains three data tables: large fires (300 acres and greater) under state and contract counties DPA, large fires (300 acres and greater) under other agencies DPA, and the number of fires and acres burned by size and cause in contract counties. We did not use the third table, but we compiled the first two tables to obtain a list of large fires. We deleted the vegetation variable because of discrepancies in the data and replaced it with a topography variable that we created. To populate the topography variable, we identified the county in which a fire had occurred and used a topographical map of California to determine the topography for that observation. We decided to delete the fatality variable as well because it lacked data for most fires. At the end of this process, we had 12 “Large Fires for All DPA” data tables, one for each year from 2008-2019, with information regarding fire names, the counties in which they occurred, their start and end dates, the acres burned, the cause, the topography, and the structures damaged and destroyed.

The second major category of the redbook, wildfire damage from Cal Fire, is separated into three subcategories: number of fires, number of acres burned, and dollar damage. Within each subcategory are multiple data tables with variables including county, size in acres, cause, and vegetation type. We ultimately used only one data table: dollar damage by size and by county, divided into seven size ranges. Having previously decided that we wanted to focus on major fires, we decided to only consider data under the 5000 acres or greater range, deleting all data that did not fit this constraint. However, the data provided by this table was useful in a given year if only one large fire occurred in a given county. In other words, if multiple large fires occurred in a given year in a given county, we could not break down the dollar damage on an individual fire basis. We cross-referenced a “Large Fires for All DPA” table of a

given year with its respective dollar damage table (of the same year) to identify the counties in which only one large fire occurred – we then created a variable labeled damage costs to store the dollar damage information for that county. Unsurprisingly, we ended up with little usable dollar damage information because most counties had multiple large fires in a given year. We ended with 12 “Large Fires for All DPA” tables, one per year, each with the additional variable of damage costs.

Next, we compiled our 12 separate “Large Fires for All DPA” tables into one table with an additional variable called year. This table had a total of 183 observations and 11 variables. Many fires lacked data regarding structures damaged and destroyed and dollar damage, so we referred to reputable news sources to find the missing information. Although this search did yield results, we still had fires for which we lacked damage costs. Despite contacting multiple agencies including Cal Fire, FEMA, the USFS, and local fire departments, we were unable to obtain some damage costs, but our data reflect the information that is currently available. We further narrowed the 183 fires in our dataset down to the ones we considered to be major. We defined a major fire as one that destroyed more than 150 structures because we realized that for fires with 150 or more structures destroyed, the damage costs were significantly greater. Our final narrowed dataset included 20 major fires with dollar damage for 15 fires. Although we reached out to multiple organizations and read several news articles about the five fires with missing costs, we were unable to obtain their damage costs, but we have all other relevant data for them. These fires, however, were not notable outliers in our dataset (based on the number of structures destroyed), so we assumed that they would not significantly impact our analysis of damage costs.

To define the frequency of potential outcomes (major wildfires), we created a model of the number of major fires over time. This model projects future trends regarding the number of wildfires in the coming years. To define the severity of potential losses, we focused on the damage costs associated with these major fires and how they are changing over time using our 20-fire dataset. We also looked into what factors affect these costs in order to more successfully mitigate the damages of a wildfire.

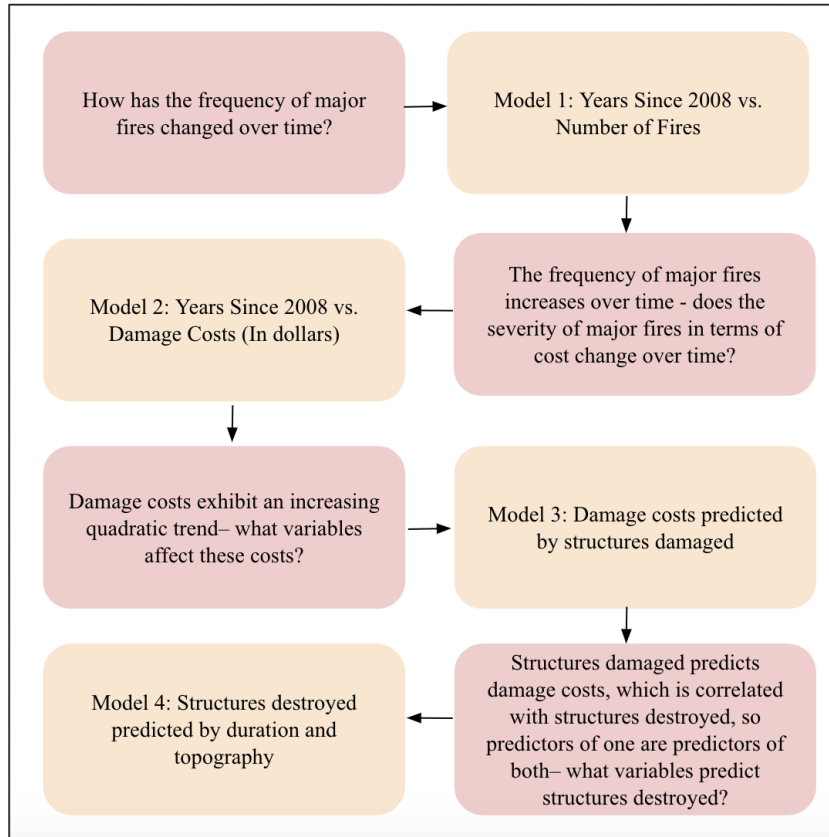
In order to investigate the factors that affect the severity of a wildfire, we introduced multiple new variables into our dataset: precipitation, El Niño years, population density, greenhouse gas emissions, duration, acres burned per day, and season. We used the date variables in our dataset to define duration as the number of days between the start date and containment date of a fire. We found the population densities of each observation with data regarding county land and population– we determined the population of the observation’s county during the year of the fire, and then divided this population by the acres of land the observation’s county had. We obtained precipitation data from the National Oceanic and Atmospheric Administration and determined acres burned per day by dividing the acres burned variable by our new duration variable. Our final 11 variables were year, start date, end date, season, county, topography, cause, duration, structures damaged, structures destroyed, and damage costs.

We recognize that a dataset with merely 20 observations lacks credibility, especially since we are attempting to identify and predict trends over time. Due to Cal Fire's evolving recording systems and procedures, we do not have access to detailed data about major fires for years before 2008. With more comprehensive historical data, we would be able to make more accurate predictions about the effects of major fires over time. Additionally, data regarding damage costs are limited, so we could only obtain costs for 15 of the 20 wildfires, which further detracts from our credibility. However, the dramatic costs associated with these fires outweigh the concerns about the integrity of our data. As residents of California, we are extremely passionate about the mitigation of major wildfires and this data set is the most credible and comprehensive source available.



## Mathematics Methodology and Analysis

The heavy financial toll of repair in the aftermath of a fire is a major concern for all of our stakeholders, from homeowners to local governments and insurance companies. Cost, especially, is the most important variable for insurance companies and government agencies to analyze, given that they pay a significant portion of the damages. Therefore, our primary goal in creating models is not only to predict these costs over time but also to suggest major contributors to cost. Below is a flowchart illustrating the progression of our models:



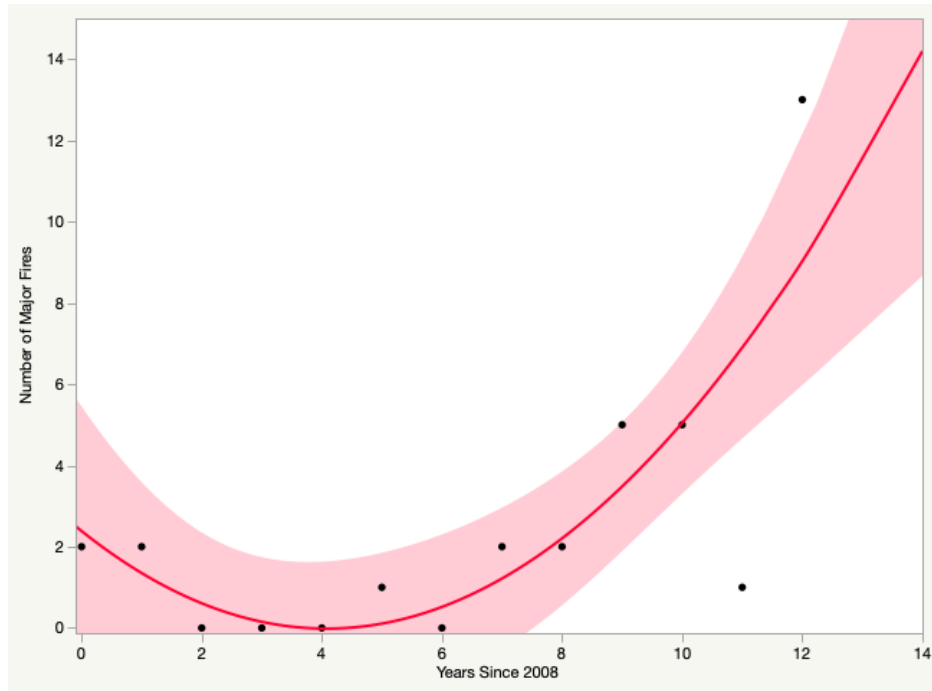
While homeowners are stakeholders in our project, we are not modeling costs associated with individual homes as the number of residences destroyed by a fire is not readily available. However, we will consider homeowners as we conduct risk analyses and present our final recommendations.

For our models, we use major fires to predict and analyze the severity and impacts of the overall fire season, since major fires (fires that destroy over 150 structures) account for the majority of the structural damage and cost per fire season. However, our strategy of only using major fires does not account for the <10% of structures damaged and destroyed that come from minor fires, and an even smaller proportion of the total costs (*Cal Fire*, n.d.). Our mathematical models assume that this percentage of structures has an insignificant impact on the overall trends. This assumption allows us to perform a more in-depth analysis because we have more data on just major fires than we do on the overall fire season. Therefore, we feel our assumptions are justified and allow for a more robust analysis of the California wildfire season.

## Model 1

Our first mathematical model explores the relationship between the number of major fires per year and time.

Model 1: Years Since 2008 vs. Number of Major Fires



We apply a parabolic fit, as there is a very clear pattern where the number of major fires per year decreases until 2012, at which point it rapidly increases. The equation for this model is:

$$\text{Number of Major Fires} = -2.81 + 0.555 * \text{Years\_Since\_2008} + 0.144 * ((\text{Years\_Since\_2008}) - 6)^2.$$

The  $R^2$  for this model is 0.64, indicating that the fit is fairly moderate. At a confidence level of 90%, the confidence interval for the *Years\_Since\_2008* parameter is  $0.555 \pm 0.286$ , and the confidence interval for the  $(\text{Years\_Since\_2008}) - 6$  parameter is  $0.144 \pm 0.0863$ .

We include the major fires from the 2020 fire season in this graph to extend our time range. The number of fires and structures destroyed are available for the 2020 season, so we are able to identify the major fires in 2020 and use them in our model. Unfortunately, because the 2020 season just concluded, the damage costs of these major fires are still being calculated, so we cannot use these fires in our cost models below (Models 2 and 3).

The minimum of the quadratic model lies near 2012 (four years since 2008). When exploring possible explanations for this minimum, we investigate the trends of California's droughts. Since 1999, the West has been "gripped in what scientists consider a 'megadrought'" that has "been interrupted by only occasional years with above-average precipitation" ("After Another," 2021). In other words, the majority of our data is representative of wildfire activity in drought conditions. The state came out of an

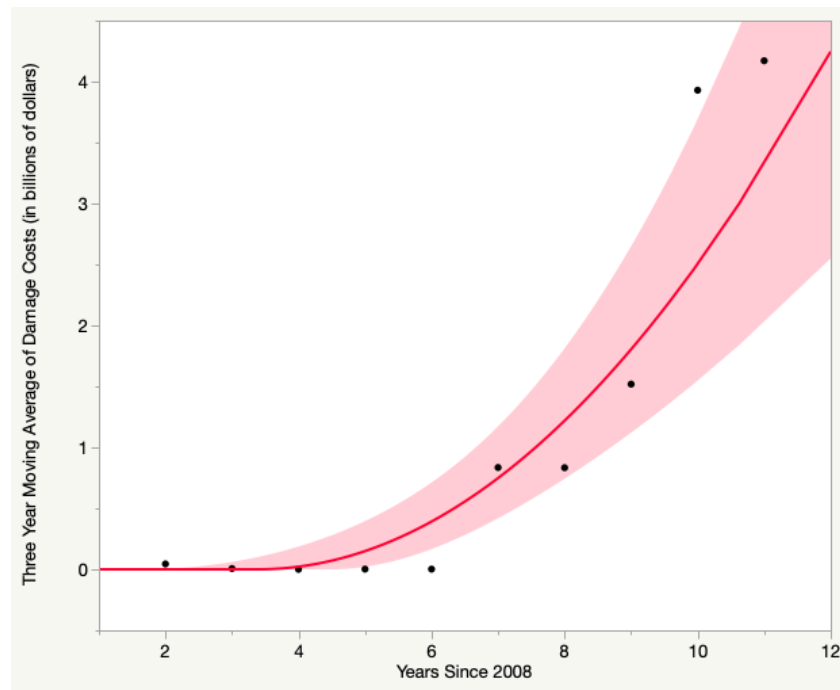
extended drought mid-2010 before entering another extended drought toward the end of 2011 that lasted until early 2019. California started to experience a drought again in 2020. The location of the minimum occurs around 2012, which was a drought year, but 2010, 2011, and 2012 all experienced zero major fires. Although our data does not perfectly correspond with the drought data, it is clear that the number of major fires dropped to zero during, or very near, a non-drought period. We find that the increasing number of fires after 2011, with the exception of 2019, is consistent with the increasing intensity and duration of California's drought. The low number of fires in 2019 is inconsistent with the rising trend of major fires, but also corresponds to a non-drought year. There appears to be a definite relationship between drought and the number of fires: non-drought years seem to yield a lower number of fires than drought years. It is worth noting that California has been in a drought for a majority of the years since 2001 although there are a few breaks (2005, 2006, and 2007 were non-drought years; mid-2010 to the end of 2011 and early 2019 to early 2020 were also drought periods, 2019-2020) between long stretches of drought.

Our data, therefore, is primarily reflective of fire frequency and severity during a drought, which, as expressed earlier, is likely different from what would occur in a non-drought period. Hence, all our models may not be responsive to the trends of non-drought years. This is important to keep in mind when thinking about projections for future fires because our projections will likely be valid only for drought years. The 2019-20 water year, however, was extremely dry in Northern California, leading many to believe that California will be in yet another multi-year drought ("Is California," 2020). Additionally, a study conducted by a UCLA geography professor indicates that the "drought in California could last indefinitely, with the resulting arid conditions becoming 'the new normal' for the state" (Bloom & Spillman, 2016). Although these drought projections are always subject to change, we believe that our predictions are likely valid for the foreseeable future, considering that many studies predict California's drought will continue.

## Model 2

Next, we create a model to analyze the damage costs associated with the rising number of fires over time. However, we realize that there is significant year-to-year variability in our data, which makes discovering trends extremely difficult. To offset this variability, we use a moving average method to model the relationship between years and damage costs. The model takes an average of the damage costs of the current year as well as the two previous years to determine the final damage costs of the current year. Each of the damage costs used is weighted equally. Using moving averages accounts for the effects of historical trends on present costs, making the overall trend visible. The resulting model is a graph of years since 2008 vs. damage costs, demonstrating how rapidly costs of fires are increasing.

Model 2: Years Since 2008 vs. Damage Costs



Model 2 applies the following nonlinear fit to represent the correlation between time (in years since 2008) and damage costs:

$$\sqrt{\text{Damage Costs}} = -0.809 + 0.239 * \text{Years\_Since\_2008}$$

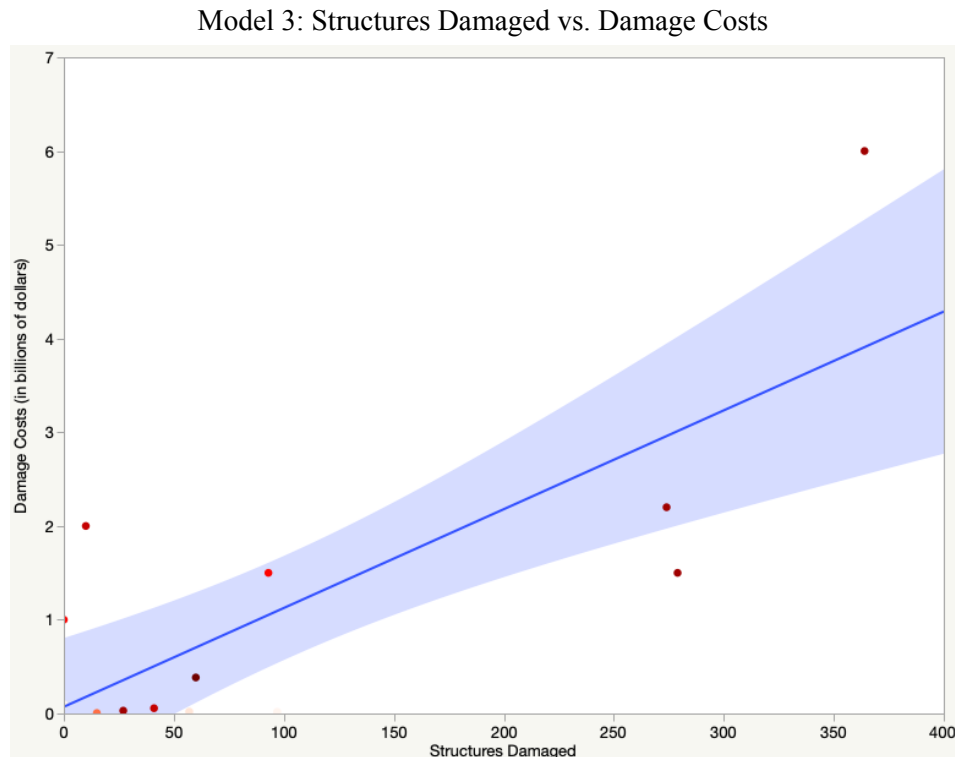
The model has a positive, strong, nonlinear relationship. The  $R^2$  is 0.82, revealing that 82% of variability in the damage costs is explained by this model. From personal experience, we know that the size and scale of California fires has been steadily increasing; logically, we expect the damage costs to similarly rise. Our graph confirms this hypothesis, as the model reveals that the damage costs are rising at an increasing rate over time. The ability to predict this cost from time allows insurance companies to better prepare for the years ahead, and also forces Californians to recognize the possibility of even more record-breaking wildfires in the near future. The confidence interval for the year parameter is  $0.239 \pm 0.0659$  at a confidence level of 90%. Originally, we used a logarithmic transformation to model the damage costs; however, the results were too extreme and unfeasible, so we used a square root transformation instead. One constraint of this model is the limited number of major fires. With more comprehensive historical data, we would be able to make more accurate predictions about the effects of major fires over time. Despite these constraints, this model accurately represents the years it does span and also fits with our anecdotal experience of the increasing severity of California fires.

This model is appropriate for predictions in the near future (~5 years), as it is unlikely that policies to mitigate the fires will have enough of an effect in such a short period of time. When considering the predictions that this model makes, it is important to note once again that the data informing this model primarily consists of wildfires, and consequently damage costs, that took place during drought years. Therefore, projections made by this model are reflective of what we would expect

during a drought. Although, as mentioned before, there are periods within our time frame during which California came out of a drought, these periods were short. Additionally, using a moving averages method smooths the effects of these non-drought periods. Thus, it is especially important to keep in mind that predictions of damage costs may only be applicable during drought periods.

### Model 3

After establishing that damage costs are on the rise, we identify some of the predictors of these costs. The data points are colored by year; the darker the point is, the more recently the fire occurred.



This model depicts a positive linear relationship between damage costs and structures damaged:

$$\text{Damage Costs} = 0.0712 + 0.0105 * \text{Structures Damaged}.$$

The darker points are generally further away from the origin, indicating higher damage costs for recent fires. This pattern corroborates the findings of Model 2: the damage costs of fires have been increasing over the last decade. The  $R^2$  for our model is 0.59, indicating a moderate fit with the model explaining 59% of the variation in damage costs. The confidence interval for this model is  $0.0105 \pm 0.00431$ . The model suggests that each structure damaged adds approximately \$11 million to the overall damage costs.

One unusual feature of this graph is the group of fires that seem to cost no money despite damaging dozens of structures. It is important to note that these fires actually cost millions of dollars; however, when comparing them with fires like the Thomas Fire and the Cascade Fire, which cost billions of dollars, they seem insignificant. In reality, these lower-cost fires still take a heavy toll on our

stakeholders as they do cost millions of dollars and must be taken into consideration when making recommendations for mitigation.

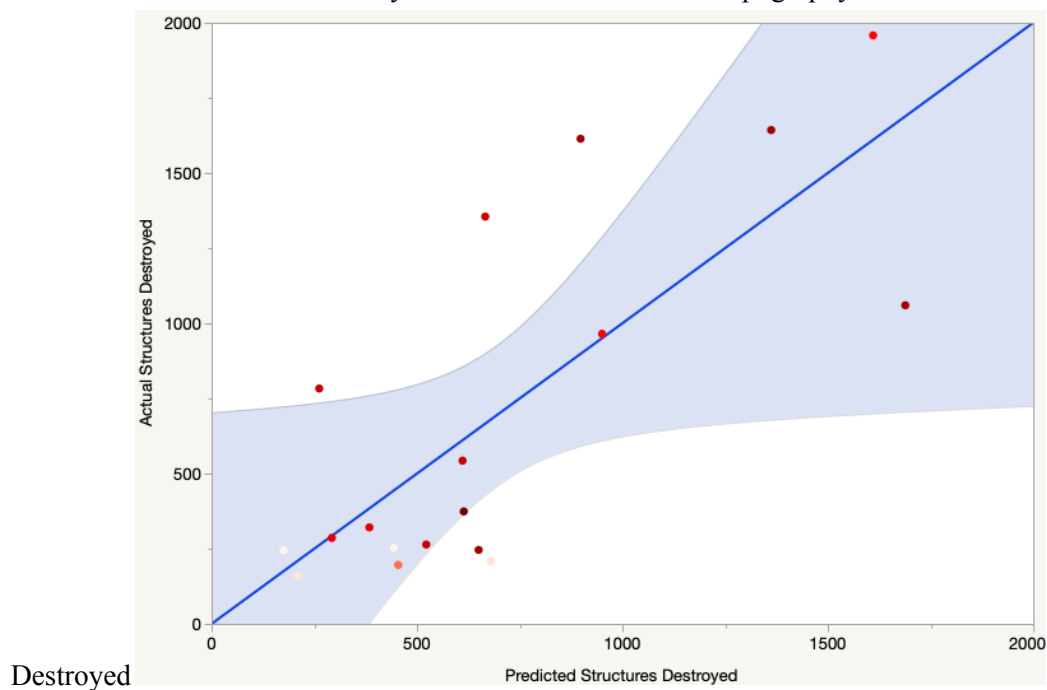
Furthermore, this model does not consider destroyed structures, and so fires that seem to have damaged no structures appear to cost billions of dollars. However, these fires actually destroyed hundreds of structures: for example, the Butte Fire cost \$1 billion and did not damage any structures, but it destroyed 965 structures. In order to try to account for the effects of structures destroyed on damage costs, we created a multivariate model using both structures damaged and structures destroyed to predict damage costs. We found that the correlation between the predicting variables and damage costs increased to 0.62, which is not much higher than that of this model. However, we felt that this increase was not significant, and because structures damaged and structures destroyed are correlated, a multivariate model introduces needless complications.

We assume that each fire event is independent. Since the major fires occurred in relatively separate zones, and Cal Fire considered each of the major fires as independent events, we determined that for our purposes, the fires can be considered as distinct events. We also assume that the counties in which the major fires occurred are at similar levels of development and urbanization. In making this assumption, we regard all the counties as having similar numbers of structures and similar qualities of infrastructure.

#### Model 4

Based on Model 3, we can deduce that structures damaged is a good predictor of damage costs. Therefore, we decide to examine the variables affecting the number of damaged structures to narrow down the factors contributing to damage costs. As destroyed and damaged structures are correlated ( $R^2$  of 0.53), we chose to examine the predictors of structures destroyed as indicators of structures damaged.

Model 4: Predicted Structures Destroyed based on Duration and Topography vs. Actual Structures



The model applies a linear fit:

$$\text{Structures Destroyed} = 406 + 13.1 * \text{Duration} + \text{Topography}.$$

*Topography:*

$$\text{Chaparral} = 773, \text{Desert} = -323, \text{Grassland} = -27.5, \text{Mixed conifer} = -30.5, \text{Oak woodland} = -392.$$

Duration and topography are the best predictors of structures destroyed, displaying a positive linear relationship with an R<sup>2</sup> of 0.58. When either topography or duration is removed from the model, the R<sup>2</sup> drops to 0.40, suggesting that the combination of the two variables best predicts structures destroyed. The following is the confidence interval for the model:

Model 4		90% Confidence Interval	
Parameter	Value	Lower Bound	Upper Bound
Duration	13.1	3.83	22.3
Topography (Chaparral)	773	535	1,010
Topography (Desert)	-323	-563	-82.5
Topography (Grassland)	-27.5	-249	194
Topography (Mixed conifer)	-30.5	-225	164

The grassland and mixed conifer topographies include zero within their lower and upper bounds, indicating that there is a possibility that they hold no predictive power. Chaparral is the only topography with a positive value, which indicates that a fire in a chaparral county will most likely destroy more structures than a fire in any other county. Given that two of the chaparral counties are Los Angeles and Ventura, the first and thirteenth most populous counties respectively in the state of California, chaparral's positive value makes logical sense. Furthermore, for every additional day in duration, this model predicts an average increase of 13 structures destroyed when all the other variables are held constant. One assumption we make in our analysis of topography is that the wildfire identified burned mostly, if not completely, within the identified county. Since our topography variable is based on the county identified, if a fire burned a significant number of structures outside of the county, there is a chance that it burned beyond the single topography identified. However, we feel like this is a reasonable assumption to make as there were very few fires that actually did burn in multiple counties. For these few fires, the acres burned and structures damaged within the identified county with significantly greater than the other counties burned.

### Outliers

We excluded two significant fires from our models due to their considerably larger order of magnitude as compared to all the other major fires. These fires are the Camp (2018) and Tubbs (2017) Fires, summarized in the table below:

Table 1: Outliers vs. Other Major Fires

	Year	Structures Destroyed	Structures Damaged	Cost (in billions of dollars)
Camp Fire	2018	18,800	754	16.5
Tubbs Fire	2017	5,640	317	10
Other Major Fires Median (Range)	2008 - 2019	348 (160 - 1958)	49 (0 - 364)	0.725 (0.005 - 6)

In analyzing these values, we find that the Camp and Tubbs Fires are an order of magnitude greater than the other major fires. The Camp Fire destroyed around 55 times the median number of structures destroyed by other major fires, and the Tubbs Fire destroyed 16 times as many structures. Furthermore, the Camp Fire cost over 22 times the median cost of other major fires, and the Tubbs Fire cost over thirteen times more. Clearly, the outliers are significantly more destructive (in terms of structures destroyed) and expensive than other major fires.

Evidently, the Camp and Tubbs Fires drastically differ from other major fires; therefore, we investigated what makes them so different. We realized that these two are the only fires that burned through entire towns or cities— the Camp Fire devastated the town of Paradise, and the Tubbs Fire damaged large parts of the city of Santa Rosa. The large amounts of urban land burned by these fires explains both the high numbers of destroyed structures and the tremendous costs associated with these outliers. Furthermore, Paradise had a population of around 26,000 people in 2018, and Santa Rosa had a population of around 174,000 people in 2017. Highly populated areas have more structures, so these fires could burn more structures in a short period of time, drastically increasing the damages and costs. However, while these fires are outliers, they make up 66% of the destroyed structures and 64% of the damage costs in our dataset. We must keep in mind that these fires have the potential to ravage entire cities and increase wildfire costs dramatically. Additionally, these devastating fires have been occurring more and more frequently; the Camp and Tubbs Fires occurred in 2018 and 2017, and the only other fire to achieve such a high level of damage was the Tunnel Fire in Alameda in 1991. Of the top twenty most destructive California wildfires, only two occurred before 2000 and twelve occurred within the last five years (*Top 20 Most*, 2020, p. 1). Thus, these two outliers are important to consider, so we explored their effects on our models.

When outliers are included in Model 2 (damage costs over time), the relationship remains positive, strong, and nonlinear. The  $R^2$  decreases from 0.82 to 0.77, suggesting that the model explains less of the variability in damage costs than it does when the outliers are excluded. The correlation coefficient also decreases from 0.91 to 0.88, implying that the inclusion of outliers weakens the correlation between year and damage costs, although the correlation is still strong. The confidence interval at a confidence level of 90% changes to  $0.421 \pm 0.132$ , indicating that including the outliers leads to less precise estimates of damage costs. In analyzing the outliers, however, it is important to note that their impact is diminished due to the application of moving averages, as this method reduces the influence of any single data point.

The predicted damage costs including the outliers are extremely high as compared to the model without the outliers (the maximum cost excluding outliers was \$3.32 billion while the maximum cost



including outliers was \$9.33 billion), demonstrating that just one devastating wildfire can significantly impact the damage costs in a year. Therefore, if the frequency of these devastating wildfires does increase in the coming years, the overall damage costs will increase at a much higher rate than our model without outliers predicts.

When the outliers are included in Model 4 (structures destroyed based on duration and topography), the  $R^2$  for the model drops from 0.58 to 0.30. The p-values for the predicting variables provide some insight into the difference in which variables hold the most predictive power between the model with outliers and the model without. With outliers, the duration variable has a p-value of 0.0848 and therefore does not hold significant predictive power, and yet, the various topographies have higher p-values that indicate far less predictive power. In contrast, the topography variable holds more predictive power in the model excluding outliers: the chaparral topography has a p-value of 0.0007. These differences in predictive power speak to the influence of the Camp and Tubbs Fires as outliers and are apparent in the confidence intervals as well. Below is the confidence interval for the model including outliers:

Model 4 (with outliers)		90% Confidence Interval	
Parameter	Value	Lower Bound	Upper Bound
Duration	136	62.8	210
Topography (Chaparral)	-872	-2,960	1,210
Topography (Desert)	-324	-2,450	1,810
Topography (Grassland)	3,020	1,310	4,740
Topography (Mixed conifer)	-1,320	-3,030	382

With the outliers, the lower and upper bounds of the chaparral, desert, and mixed conifer topographies hint at a lack of predictive power. In this model, grassland has by far the greatest and only positive value. This is likely because the Camp Fire, a major outlier and grassland fire, destroyed enough structures to warrant this discrepancy. Additionally, for every one day increase in duration, this model predicts an average increase of 136 structures destroyed, a notable increase from the thirteen structures destroyed in the model without outliers. The outliers have a significant impact on the variables with the most predictive power - duration and the grassland topography.

We believe these devastating wildfires may continue in following years as the data available from the 2020 fire season indicates at least one devastating wildfire occurred. Additionally, as these devastating wildfires have only started occurring since 2017, we do not have the necessary data to analyze historical trends to predict their future frequency and severity. Although we exclude outliers in our models due to these issues, we must keep in mind that these devastating wildfires have been occurring more frequently in recent years and have the potential to significantly increase damage costs and structures destroyed.

## Risk Characterizations

Our next step is to use the models to predict the severity and frequency of major fires over the next five years. It is important to note that in making our predictions, we assume drought conditions. Therefore, our predictions are only valid assuming the years to come are drought years since our models may not be responsive to the trends of non-drought conditions. We begin by using Model 1 to predict the frequency of major fires, rounding to the nearest integer:

$$\text{Number of Major Fires} = -2.81 + 0.555 * \text{Years\_Since\_2008} + 0.144 * ((\text{Years\_Since\_2008}) - 6)^2.$$

Table 2: Predicted Number of Major Fires Sensitivity Analysis (assuming drought years)

Confidence Interval for Parameter: 0.144 ± 0.0863					
Year	2021	2022	2023	2024	2025
Prediction	12	14	17	21	24
Minimum	7	9	10	12	14
Maximum	16	20	24	29	35

As the calculations show, in a mere five years, the frequency of major fires will double. Based on these projections, the number of major fires in 2025 will be 12 times greater than the number of major fires that occurred in 2008. Even the minimum numbers of major fires are relatively high, demonstrating the importance of mitigation. Our predictions are fairly credible, given the small range of possible values. The significant increase in the number of major fires over time threatens not only the homeowners' safety, but also the financial stability of the insurance companies and government agencies; a surge in the number of fires indicates a surge in the damage costs attributed to these fires as well. We use Model 2 to project these damage costs:

$$\text{Damage Costs} = (-0.809 + 0.239 * \text{Years\_Since\_2008})^2.$$

Table 3: Predicted Damage Costs of Major Fires Sensitivity Analysis (assuming drought years)

Confidence Interval for Parameter: 0.144 ± 0.0863					
Year	2021	2022	2023	2024	2025
Prediction	5.29	6.45	7.72	9.10	10.6
Minimum	2.08	2.61	3.20	3.85	4.56
Maximum	10.0	12.0	14.2	16.5	19.2

Our model predicts that between 2020 and 2025, the damage costs of major fires will virtually double, increasing by \$5.3 billion. According to our calculations, the damage costs between 2024-25 will be approximately 150 times greater than the damage costs between 2008-09. The sensitivity analysis reveals that the ranges for each of the predicted costs are quite large and thus detract from the predictions' credibility and hinder accurate cost projections. Based on our calculations, it is important to note that both the minimum and maximum damage costs for each prediction are high. Therefore, any cost in the range of the predicted values would significantly impact our stakeholders, demonstrating the importance of implementing effective mitigation strategies quickly.

These predictions do not take into account the county in which a fire may burn or the types of structures it may destroy. Commercial buildings are known to be more expensive and time-consuming to construct in comparison to residential buildings, so a fire that burns ten commercial buildings could be more costly than one that burns 20 residential buildings. Buildings also vary in cost depending on the locations in which they are constructed. However, data regarding the breakdown of the types of structures destroyed by a specific fire is not available, and hence we are limited in our ability to further analyze these damage costs. Regardless, the enormous predicted values for damage costs indicate great risk with large potential for loss. We must also recognize that these major fires occurred irregularly over the last few decades. The drastic increase in the frequency of major fires over the past 12 years complicates the analysis of these fires, especially in terms of discovering historical trends. However, due to the sheer destruction these fires create and the costs to repair this damage, analyzing these fires is of the utmost importance. We believe creating targeted mitigation strategies for these major fires will reduce most of the damages caused by wildfires in the future.

One major intrinsic issue of our study is the variability in the data, and the consequent inability to classify the data efficiently. Structures destroyed and damage costs have a significant correlation, but there are anomalies that alter our analysis and predictions. For example, all major fires that destroyed under 500 structures cost less than \$2 billion. We had hoped to classify fires in this way, and our goal was to classify the remaining fires such that fires that destroyed between 500-1000 structures would cost \$2 billion-\$2.2 billion. However, the Butte Fire in Amador County destroyed 965 structures and still costs less than \$2 billion. These anomalies in our data prevented us from classifying the fires such that a fire that burned some number of structures would then cost some number of dollars. The inherent variability in natural disasters like wildfires causes this unpredictability in classification, and therefore limits some of our analysis and the accuracy of our predictions.

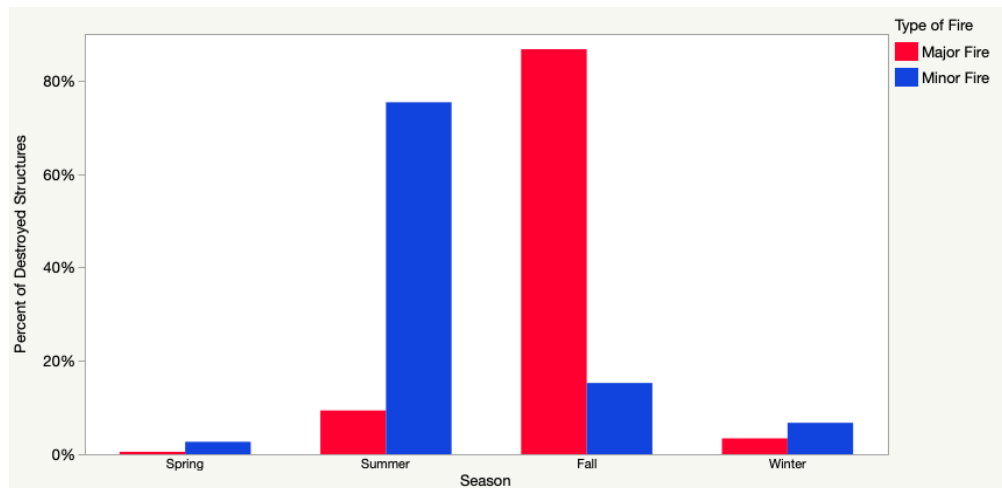
With regards to risk distribution, identifying the distribution for major wildfires is difficult as each of these fires is an extreme loss. Major wildfires cannot be categorized or classified easily as, by definition, each of them pose significant risk to our stakeholders. Thus, the distribution of risk is not a gradient of small and large risks; rather, it is the possibility of one of these major wildfires occurring as each of them poses large risks. There are some extremely devastating wildfires that we have decided to exclude from our predictions. According to our entire dataset, these extreme wildfires pose large risks, but have low probabilities of occurring frequently in a given year.

Due to the lack of a clear classification of major fires, we chose not to calculate expected value in order to best represent our data. Instead, we calculated the means and standard deviations of damage costs and structures destroyed, as these are our two main dependent variables in our 20 major fires dataset. When excluding the outliers, the mean for damage costs for our twenty fires is \$1.17 billion and the standard deviation is \$1.60 billion. The large value for standard deviation is due to the variability in our data for damage costs. Since the standard deviation is larger than the mean, our values for the mean have

little credibility and are not useful in making predictions. By contrast, the mean of structures destroyed was 824 structures, and the standard deviation of structures destroyed was 690 structures. Although the standard deviation is still extremely high, there is slightly more credibility since the values within the range would all be positive. For both structures destroyed and cost, the mean values reported here are significantly greater than the median values we reported in Table 1, demonstrating the right-skewed nature of the distributions.

Our cost model, Model 2, predicts significant financial loss, but these costs can be minimized with risk mitigation strategies. In order to suggest some strategies, we conduct further analysis to find patterns among the timings, locations, and causes of the major fires in our data. In looking at when major fires tend to occur, we decide to consider timing based on season. The following distribution compares the percent of minor wildfires that burned in each season with the percent of major fires that burned in each season.

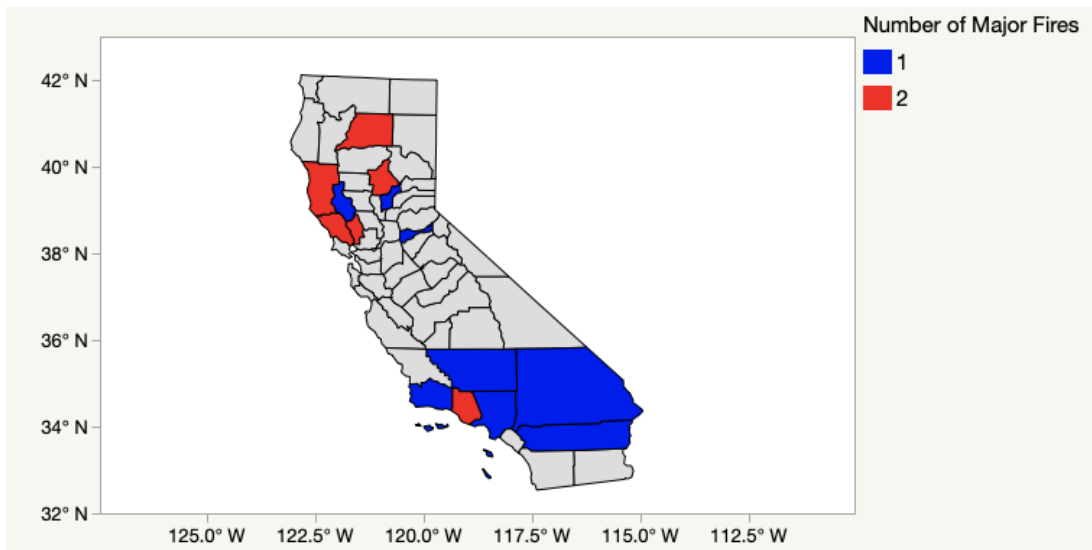
Model 5: Season vs. Percent of Structures Destroyed by Type of Fire



We created this graph using both our major fires dataset and the dataset that contains 183 observations (both major and minor fires). Notably, the vast majority of structures destroyed by major fires were destroyed in the fall, while most structures destroyed by minor fires were destroyed in the summer. The graph indicates that more structures are destroyed by major fires in the season of fall; thus, fall conditions seem to be a hazard that increases the risk of destruction by major fires. Since we know that major fires account for almost all of the damage costs and structures destroyed each year, we can conclude that more resources should be allocated to the fall fires, as the majority of highly destructive fires can be attributed to this time of year.

Next, we explore common locations of major fires based on our data. The following map of California indicates counties where major fires have occurred between 2008 and 2019.

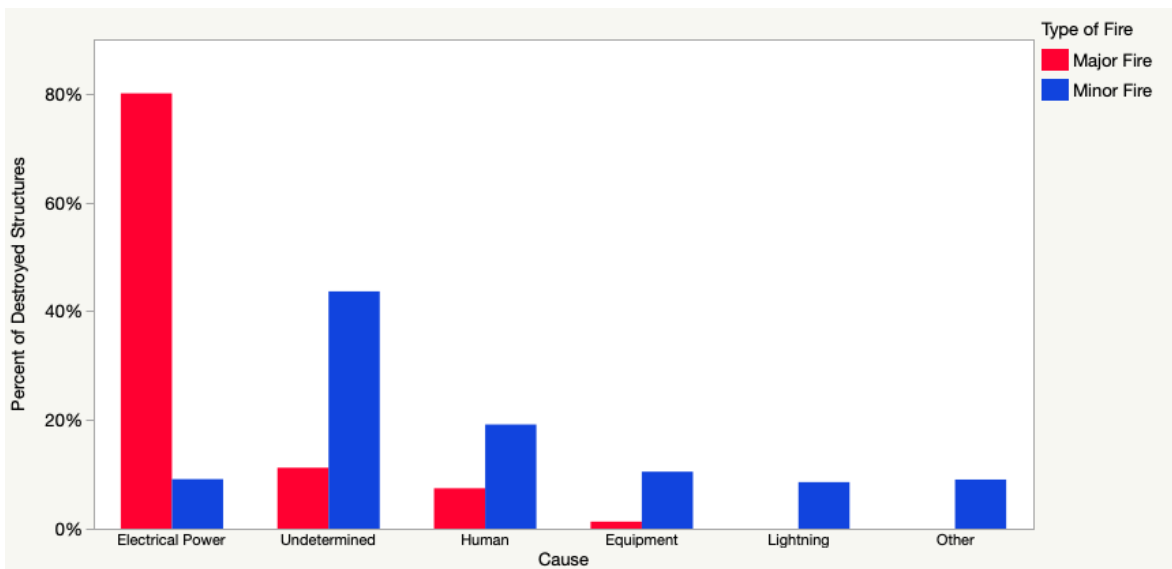
Model 6: California Counties Colored by Number of Major Fires



One notable overall trend in this graph is that northern counties tend to have more major fires than southern counties. Five northern counties experienced two major fires in the last twelve years as opposed to one southern county. The sum of major fires in the north is thirteen fires, while the sum of major fires in the south is seven fires. Based on this graph, fire departments may need to consider devoting more resources to the northern counties as they have more total major fires. Additionally, many counties have not experienced a major fire in the past decade, suggesting that their manpower and resources can be redirected to counties that are in greater need. To explore the reasons behind the impact of location on major fire frequency, additional research beyond the scope of this project is required.

We also explore causes for wildfires: the following distribution depicts the percent of structures destroyed by a certain cause, and is colored by major and minor fires.

Model 7: Cause vs. Percent of Structures Destroyed by Type of Fire



The model highlights the following causes of wildfires: electrical power issues, human activity, failure of mechanical equipment, lightning, and other, which includes vehicles and arson. These causes are the primary hazards that create the risk of structures destroyed by wildfires. The two causes that generate the most destroyed structures by major fires are undetermined and electrical power: electrical power issues account for around 80% while undetermined issues account for around 10%. The sheer scale of structures destroyed by electrical power fires (70% more than fires due to undetermined causes) is striking and must be mitigated. Undetermined fires account for far less destruction and are much harder to mitigate because the causes of the fires are unknown, so they are not the focus for our recommendations. Additionally, the Camp and Tubbs Fires, the two most destructive fires in the dataset, are both attributed to electrical power, demonstrating the destructive potential of electrical fires.

Based on these projections, we have identified the following types of fires as the most requiring of resources: fall fires, northern fires, and electrical power-caused fires. Additionally, fall, northern, electrical-caused fires account for 50% of the structures destroyed by all major fires between 2008 and 2019: clearly, these three hazards increase the risk of not only a wildfire occurring, but also of the extent of damage that a wildfire causes. It is also worth noting that the Tubbs Fire, one of the most destructive and deadliest California fires in history, falls under all of these categories, as does the Camp Fire, the only fire to surpass the Tubbs Fire in structures destroyed. Because these two outliers are both northern, fall, and electrical-caused fires, when we include them in our analysis, we find that the structures destroyed by this specific category of fires increases to 83%. Evidently, with or without outliers, the northern, fall, and electrical hazards strongly affect the number of structures destroyed, thus allowing us to narrow the scope of our recommendations to a very specific category of fires.

When thinking about who absorbs the greatest amount of risk, the cause and location of a fire are important determinants. For electrical fires caused by malfunctions in equipment belonging to electric companies, insurance companies do not absorb nearly as much of the risk as the electric companies do. When the cause of a fire is natural or unknown, however, insurance companies absorb a majority of the risk. Depending on the location of a fire, state governments also absorb risk because they bear the responsibility of repairing destroyed infrastructure or public property. Major fires also tend to require federal funds, and therefore, the federal government also absorbs some of the risk. It is worth recognizing that federal and state funds are geared toward suppression costs rather than damage, or repair, costs (Adler, 2018). Insurance companies are responsible for handling many of the damage costs because of the large numbers of homes and other properties that burn, so they generally suffer the most in terms of risk. In addition to governments and insurance companies, homeowners are also stakeholders in the event of a fire. They arguably absorb the most risk, albeit a different kind of risk: an emotional kind. While they also suffer a financial loss, there is a huge emotional element to losing a home as the result of a fire. Although this risk cannot be quantified, it is prominent and devastating for many homeowners—they lose the memories and sentiment associated with their properties.

## Recommendations

First and foremost, in order to modify the outcome of severe structural damage, we highly recommend better electrical infrastructure management, specifically undergrounding more transmission lines and covering conductors.

When investigating California's electrical infrastructure, we identified two types of power lines: transmission lines and distribution lines. Transmission lines are rated at much higher voltages because they carry power from power plants to distribution units. Distribution lines then carry lower voltages of power from the distribution units to residential and commercial areas. Since transmission lines are higher voltage and thus more dangerous, we decided to focus on mitigating the damage caused by these lines. Furthermore, transmission lines typically lie in areas prone to wildfires while distribution lines exist in more urban areas (*Transmission Vs. Distribution*, n.d.).

One of the most effective ways to manage transmission lines and prevent electrical wildfires is undergrounding, or replacing overhead transmission lines with underground lines. Despite its success, undergrounding is extremely expensive: it typically costs between \$3.4 million and \$6.1 million to underground just one mile of power line (*CPUC Undergrounding*, n.d.). For ease of estimation, we will use the mean of this range, \$4.75 million, for our cost predictions. Another important factor to consider in the implementation of undergrounding is time: California only undergrounds up to 100 miles of transmission line per year; however, Pacific Gas and Electric (PG&E), California's main northern electricity provider, only undergrounds 30 miles of lines per year (*Electric Undergrounding*, n.d.). Since California has over 25,526 miles of transmission cables, it would take over 850 years for PG&E to underground all the lines (*CPUC Undergrounding*, n.d.). Clearly, undergrounding the whole system is costly and would not be completed in a reasonable time frame. However, based on our analysis of electrical fires, these fires typically occur in Northern California, so we recommend focusing efforts on the northern counties of Amador, Butte, Lake, Mendocino, Napa, Shasta, Sonoma, and Yuba. There are around 1777 miles of transmission lines in these counties (Thong, 2020), so if California were to only implement undergrounding in this region, it would cost around \$8.4 billion and take 59 years at PG&E's current rate. Again, these numbers are simply beyond the achievable scope, so we recommend PG&E doubles its current rate to underground 60 miles per year in order to underground the 1777 miles in around 29 years. Despite the doubled rate, the time frame is still large, as is the cost.

Covering conductors is a cheaper alternative that is virtually as effective as undergrounding in areas that are surrounded by vegetation. Covered conductors are power lines insulated with special materials to protect the lines against accidental contact by vegetation. Wildfires are most often caused by stray vegetation interacting with power lines, protecting these lines would reduce the risk of fire. If a covered power line is knocked down by a tree, less of the bare wire would be exposed to vegetation due to the insulation, reducing the chance of starting a fire. Covered conductors are also significantly cheaper than undergrounding, requiring only \$0.43 million per mile. Additionally, they take much less time to implement, and are extremely effective against many varieties of vegetation disturbances (*CPUC Covered*, 2019).

Southern California Edison, a major southern electric company in California, ran several tests on covered conductors to determine their effectiveness in comparison to bare conductors (the current power lines) and undergrounding.

Table 4: SCE’s Alternatives Mitigation Effectiveness Analysis (*CPUC Covered, 2019*)

	ODRM Cause Code	Covered Conductor Effective?	Bare Conductor Effective?	Undergrounding Effective?
Contact From Object	Animal	Yes	No	Yes
	Balloon	Yes	No	Yes
	Other	Partial (Yes for ‘Foreign Material’)	No	Yes
	Vegetation Blown; Vegetation Overgrown	Yes	No	Yes
	Vehicle Hit	No	No	Yes

While undergrounding was found effective for every possible scenario involving vegetation, covered conductors were effective for 80% of these scenarios, so this method is a feasible alternative to undergrounding (*CPUC Covered, 2019*). Southern California Edison also determined the cost to effectiveness ratio for each of these solutions.

Table 5: SCE’s Alternatives Mitigation Effectiveness Analysis (*CPUC Covered, 2019*)

Alternative	Drivers Mitigated	Cost per Mile (\$ million)	GSRP Mitigation Cost Ratio
Covered Conductor	60%	0.43	1.40
Bare Conductor	15%	0.30	0.50
Underground Relocation	100%	3.0	0.33

Undergrounding, because of its high cost, was found to have a mitigation cost ratio of 0.33 while covered conductors were found to have a mitigation cost ratio of 1.4. Covered conductors are clearly a better choice for lower-risk areas that still require significant protection from accidental vegetation contact (*CPUC Covered, 2019*).

Approximately 48% of the land in the previously listed northern counties contains high amounts of vegetation. We assume that the amount of land is proportional to the number of transmission lines, so we claim that around 48% of the 1777 miles of transmission lines are in areas with significant vegetation, for a total of 853 miles of line. Because covered conductors have proven to be effective in highly-vegetated areas, we recommend that they be used in these areas instead of undergrounding. We recommend that these 853 miles of transmission lines be modified to include covered conductors, an initiative that will cost \$367 million (\$0.43 million per mile) as opposed to the \$4.1 billion that undergrounding would cost. Since PG&E controls Northern California transmission lines, we suggest that a portion of the profits made by PG&E be directed toward the covered conductors initiative. We are aware that PG&E came out of bankruptcy in the summer of 2020; however, based on the company’s third-quarter financial results of that same year, they are making significant profits. Their non-GAAP (Generally Accepted Accounting Principles) core earnings as of September 2020 were \$1.579 billion, so they have enough money to fund covered conductor efforts in the future (PG&E, 2020).

However, for the other 52% of the land, we recommend undergrounding because covered conductors are not as effective as undergrounding in areas with less vegetation. Once again, we assume the amount of land is proportional to the number of transmission lines, so we recommend that around 924 miles of transmission lines should be undergrounded. At a cost of \$4.75 million per mile, our total cost for



undergrounding 924 miles comes out to approximately \$4.4 billion. Assuming that around 58 miles are undergrounded per year (slightly less than our suggested undergrounding rate to be conservative), the cost per year comes out to \$274 million, and the project would be completed in 16 years. Given that PG&E has 5.5 million electric customers (*PG&E Overview*, 2020), we recommend that the company increases ratepayer costs by \$4.00 per month for the next 16 years to help cover the costs of undergrounding. We recognize that increasing ratepayer costs is not ideal, but it is preferable to the far more costly alternative of repairing wildfire damages.

The increase in ratepayer costs is still insufficient to cover the total costs of undergrounding, so we recommend that the government contribute as well. California's 2020-21 wildfire prevention budget has already allotted \$492 million to proposals from various departments, including \$30.2 million to the CPUC (*Governor's Wildfire-Related*, 2020). The CPUC plans to use that money for reforming their current processes and overseeing their wildfire mitigation plans, which includes hardening their grid system, inspections, forecasting, and emergency preparedness (*Governor's Wildfire-Related*, 2020). We recommend that the CPUC contribute \$10 million of that \$30.2 million to PG&E solely for undergrounding. This \$10 million dollars, in addition to the \$264 million contributed by PG&E ratepayers, will sufficiently cover the yearly costs for undergrounding. We also propose that the government continue to provide around \$30 million per year to the CPUC for their other wildfire prevention efforts.

Upon further examination of the wildfire prevention budget, we notice that \$25 million was allocated to home hardening in the 2021 fiscal year (*The 2021-22*, 2021). However, a fire scientist with SAGE Underwriters, an insurance agency, claims that in the past few years, many homes with the latest fire-safe features still burned. Other scientists and research have attested to the decreasing effectiveness of various fire-safe building codes, and therefore, we have decided not to pursue that angle in our recommendations (Sommer, 2019). Since home hardening efforts appear to be ineffective, we recommend that the \$25 million dedicated to home hardening be redirected to PG&E in order to double the rate of undergrounding efforts.

Additionally, in order to combat future issues with transmission lines, we also recommend that the government enacts a policy to underground all future power lines in the identified susceptible areas. By ensuring that future transmission lines are underground, we can reduce the likelihood of a future fire being started by a downed power line. Furthermore, undergrounding in the initial installation of a power line is cheaper than originally implementing overhead lines and later converting. A new underground line is \$0.8 million per mile (*Facts About*, 2017), while the conversion of overhead lines to underground ones is \$4.75 million per mile. Clearly, preemptively undergrounding lines is both safer and cheaper than starting with overhead lines.

While electrical efforts are preventative, the aftermath of wildfires pose an extreme risk to insurance companies, because the sheer damage from even just one major fire can cripple an agency. The 2018 Camp Fire, for example, pushed Merced Property and Casualty Company (a Paradise insurance agency) to insolvency, hurting both the company and the homeowners. The homeowners were severely affected because their claims were capped and delayed; however, the insurance company's liquidation was the root cause of unanswered claims (Yan & Boyette, 2018). In order to protect insurance companies when wildfires do occur, we propose risk pooling as an alternative to ensure no one insurance company must bear the brunt of wildfire damages alone. Combining the strength of multiple insurance companies allows the companies to remain afloat after major fires, and ensures each homeowner's claims are paid in full. We recommend that companies that insure homeowners in northern regions pool their risks together

if the damages from a fire exceed a certain cap in order to avoid bankruptcy. We do not explore the exact range of this cap in our project, but we recommend that Northern California insurance companies separately discuss this number.

Another recommendation we propose for behavior change is government implementation of a comprehensive fire safety and preparedness program in every California public school. Currently, California's public schools are not required to teach fire safety, although the California Fire Prevention Organization has visited elementary schools in the past to educate students. They typically present for around 45 minutes to teach basic fire safety before sending students home with an inspection form that must be returned the following day for credit. In the next session, they teach students about evacuating a home in the case of a fire and all of the associated safety procedures. Finally, students meet firefighters to conclude the program (Barrett, 2020). We recommend that the government mandate a similar program in all public schools, starting with those in high risk areas. By starting with the younger generations, we can work to ensure the safety of every citizen, and encourage families to make choices with fire safety in mind. With support from the government and local communities, we believe that every school district could be implementing such a program within the next two to three years.

However, we cannot rely solely on schoolchildren to hold and apply fire safety knowledge. Therefore, we encourage community centers to offer fire safety and preparedness workshops for adults. While this will not have the same far-reaching effects as public school curriculum change, having regular workshops could help educate a significant portion of the community. The government should standardize the curriculum taught across centers, and the material can be reused from the public school program with some additions. The additions should include informing adults to cover their vents with mesh and to clear vegetation around their houses (*Fighting Wildfires*, 2019). Information regarding when the major wildfires tend to occur (fall) as well as the locations that are most susceptible (northern region) should also be conveyed along with common causes (electrical issues). We also recommend that homeowners receive the material taught by the community centers upon purchasing a home or insurance. This approach will ensure that the vast majority of houses will be ready in the case of a wildfire, reducing casualties. While the state of California does have information available to the public regarding preventative measures, we recommend that the state makes a concerted effort to ensure every Californian is wildfire-ready in order to reduce deaths and damages (*Homeowners Checklist*, n.d.).

Furthermore, a social media campaign will also be instrumental in better educating California homeowners on fire prevention, as well as quickly spread information regarding wildfires. Many other social movements have found social media to be a cheap and easy tool to spread their message, and fire departments could also make use of Twitter, Instagram, Facebook, and other platforms to ensure citizens are prepared and aware of potential fire threats. These organizations could use social media to send out emergency alerts, evacuation notices, and methods to prepare for specific fire threats. Additionally, California currently has one of the youngest populations in America (*California's Population*, 2020), and younger citizens are more likely to be active on social media. Therefore, a social media campaign would be an extremely effective strategy, especially in this state.

In order to change homeowner behavior, insurance companies either penalize failures to meet local fire safety guidelines or incentivize efforts to fire-proof homes. Currently, some insurance companies refuse to renew insurance if the applicant does not clear their brush. Additionally, some county governments fine homeowners who do not adhere to strict vegetation clearing rules (Nagourney & Fuller, 2017). Another possible approach could be to incentivize homeowner behavior change by encouraging insurance companies to discount insurance if other simple fire mitigation strategies, such as clearing

vents, are followed. Although incentivizing homeowners would be ideal, wildfire prevention and relief efforts will take up much of the government and insurance agencies' budgets, so we recommend continuing with the current fining process.

We are aware of the relationship between climate change and wildfires; according to the National Aeronautics and Space Administration (NASA), climate change is leading to hotter and drier conditions that increase the likelihood of a wildfire igniting, the intensity of a given fire, and how fast it spreads (Gray, 2019). However, we do not address mitigation techniques for climate change in this report, as we have deemed it outside the scope of this project due to the inherent variability of the issue.

Finally, we highly recommend that Cal Fire and other fire organizations improve the accessibility and breadth of wildfire data available. One of the most frustrating challenges during the course of this project was to find comprehensive, organized information on major wildfires, and this hurdle prevents more people from analyzing and making predictions based on data. We would specifically recommend the compilation, acquisition, and tabulation of all major wildfires in the last few decades, including their structures destroyed, county, damage cost, and other essential information. Currently, much of this information can be found in the redbooks; however, the individual costs of fires are hard to find and the redbooks are only for one year at a time. The information in the redbooks is also not provided in an easily transferable format, dissuading researchers and analysts from making use of this information. We strongly encourage Cal Fire to consider developing a more easily accessible and comprehensive dataset for major wildfires.

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