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Burn Probability and Climate Change: A Quantitative Evaluation of the Temporal Alterations of Wildfire

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FIRE PROBABILITY AND CLIMATE CHANGE: A QUANTITATIVE EVALUATION OF THE TEMPORAL ALTERATIONS OF WILDFIRE

THESIS

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Abstract

The intensity of extreme weather events, specifically wildfires, along the west coast has slowly grown over time due to atmospheric changes caused by climate change. The Air Force, though aware of the threat that is wildfire, does not currently have a quantitative way to assess the hazard to base locations. In this paper, burn probability is quantitatively calculated through the geospatial analysis programs to provide a means of assessing wildfire vulnerability.

The FlamMap fire simulator generated burn probabilities for Vandenberg Air Force Base using climate data generated by the remote automated weather station on the base to highlight how the burn probability has changed over time. The USGS data (Elevation, Vegetation,etc.) utilized in the model comes from the LANDFIRE Project. Results showed an increase in burn probability over time, but inconsistent overall trends. A closer look at the odd spike for the year 2009 showed that drought heavily impacted the burn probability. Further development of this framework should provide a valuable a tool to identify strategic plans for construction that align with land and missions resource objectives.

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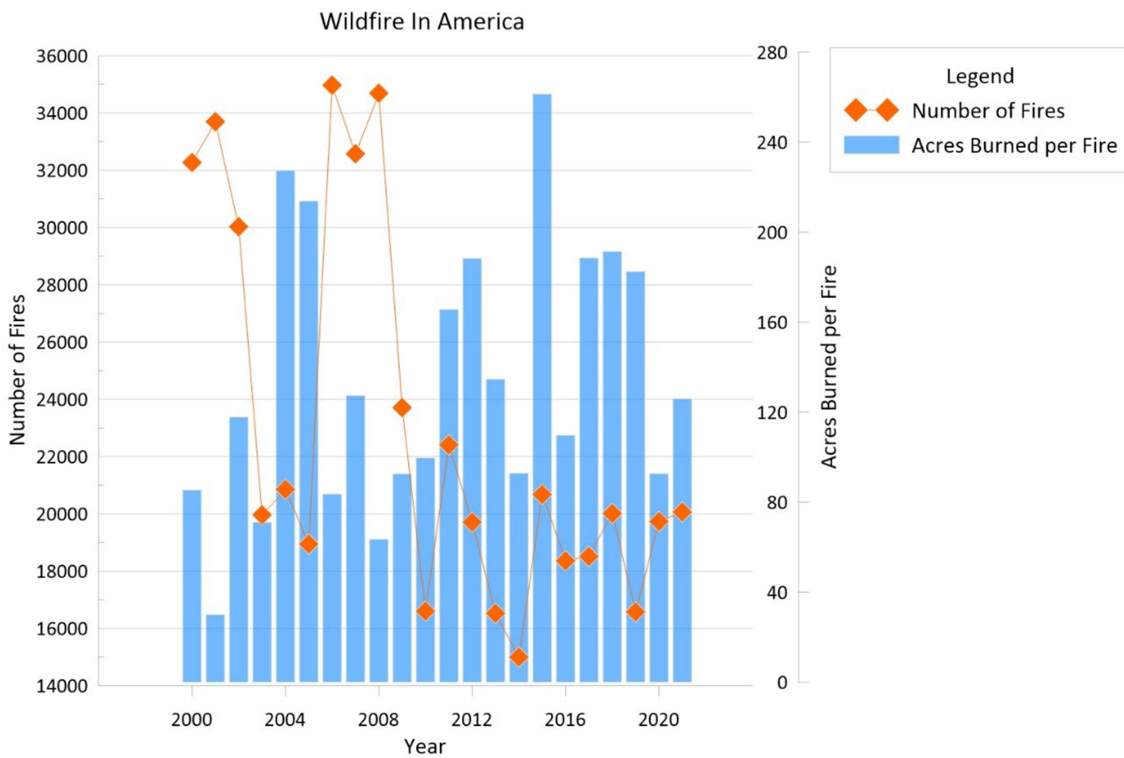
FIRE PROBABILITY AND CLIMATE CHANGE: A QUANTITATIVE EVALUATION OF THE TEMPORAL ALTERATIONS OF WILDFIRE

I. Introduction

Wildfires are uncontrolled burning using forests and grasslands as fuel [Malik, et al. 2021]. Natural occurrences like lightning have been linked to ignition of wildfires. Human manufactured events also occur. The most significant cause of concern for wildfire is how they affect society. In 2020, more than 17,000 structures were burned in wildfires, the majority of which occurred in California [Federation of America 2020]. Wildfires threaten structures, ecosystems, and natural resources that human lives use by spreading as crown fires from the tops of trees, surface fires from leaves, or ground fires caused by existing brush.

Historically, the west coast of the United States has been known to be plagued by the wildfires caused by the heatwaves and droughts that are recurrent in that region. Each year California struggles to contain fire spread and evacuate citizens in danger. During December of 2020, the Santa Ana wind event caused multiple fires to burst around Los Angeles, ushering in the largest wildfire season in California history [Malik, et al. 2021]. According to the U.S. Department of the Interior, 70% (7.1 million acres) of the nationwide acreage burned was on federal lands [California Department of Forestry and Fire Protection 2021]. National fires can be seen below in Figure 1. Through treating the lands and other fire

suppression actions, the U.S. has decreased the number of fires. The acres being affected by fires is growing.



DoD Motivation:

The "DoD manages a global real-estate portfolio with an almost $1.2 trillion estimated replacement value [U.S. Government Accountability Office 2019]". In

2019, Congress (GAO) required the DoD to conduct a study on climate resistance and extreme weather for the military installations of the government. The result was the "Report on Effects of a Changing Climate to the Department of Defense." This report showed that installations, DoD-wide, have not assessed what effects their infrastructure may face in the future. All previous planning was based on historical climate events the locations had experienced instead of future climate projections. Lack of foresight and guidance from higher up have led to this result. The recommendations to correct this issue can be summarized as:

1. The DoD should update the unified facilities criteria to state that an installation master plan must incorporate climate change assessments.
2. The Secretary of Defense should issue guidance on how the DoD should incorporate climate projections.

There were no concrete recommendations or specific steps given on how installations should combat the threat of wildfire or the other reported concerns. The report views 79 installations and gives general concerns and results for five threats seen in table one. The current and potential wildfire threat from Table 1 shows that of the 36 Air Force (A.F.) locations, 32 have potential and current issues. This means that more than 90 percent of the assessed A.F. installations are vulnerable to a wildfire incident.

Table 1: DoD Report Installation Extreme Weather Chart

Service	# Installations	*Recurrent Flooding*		*Drought*		*Desertification*		*Wildfires*		*Thawing Permafrost*	
		Current	Potential	Current	Potential	Current	Potential	Current	Potential	Current	Potential
Air Force	36	20	25	20	22	4	4	32	32	-	-
Army	21	15	17	5	5	2	2	4	4	1	1
Navy	18	16	16	18	18	-	-	-	7	-	-
DLA	2	2	2	-	2	-	-	-	-	-	-
DFAS	1	-	-	-	1	-	-	-	-	-	-
WHS	1	-	-	-	-	-	-	-	-	-	-
Totals	79	53	60	43	48	6	6	36	43	1	1

There is no graduated threat assessment or starting benchmark to how dangerous extreme weather events are to the continued missions on installations. This has led to a devastating lack of efficient infrastructure preparation on how to combat these threats. Hurricane Michael in 2018 devastated Tyndall Air Force Base (AFB) as a category five. The damage exceeded 25 million dollars, and reconstruction of the base is still ongoing. Other coastal installations are constantly at risk of flooding

Figure 2 shows the Canyon Wildfire at Vandenberg AFB, California, in September 2016 still in process. This fire burned over 10,000 acres and came close to two impacting Space Launch Complexes. This continued with a wildfire that grew to about 380 acres in 2017 and 140 acres lost in 2019. In August 2020, Travis AFB, California, had to initiate an immediate evacuation of all non-mission essential personnel as 124,100 acres of land burned [Pawlyk, O 2020]. As

a result of incidences like this, the DoD spends considerable resources on claims, asset loss, and suppression activities due to wildfire and a lack of quantitative data to plan fire mitigation [DoD 2019].

Figure 2: Vandenberg on Fire by Vandenberg Fire Department

Problem Statement

What research has been accomplished outside of the Department of Defense? Researchers around the world have been working on ways to understand fire behavior to better manage land. Different components could be modified or altered to benefit the future research of the A.F. wildfire mitigation factors.

What are the long-term effects of climate change on an installation? More to the point, what aspects of climate change will have a disproportionate impact on the infrastructure than what has been seen in the past decades. How will the missions of the installations be impacted going forward compared to before? Will mitigation efforts need to be moved to other locations now to suppress the probability of wildfire better?

193 million acres of federal land owned by the U.S. is managed by the U.S Forest Service. This organization works to maintain the land through treatments, fire suppression, and the clearing of debris that could act like dead fuel. They have focused on how the vegetation of the U.S. and how it acts like fuel. More countries are having research done to understand the wildland-urban interface (WUI) and the human interaction with wildfire. Researching wildfire interactions with society is important because the A.F. has multiple installations in urban areas that are affected by wildfires annually. The west coast of the U.S. is one of the worst affected areas. This threatens the infrastructure and the missions that those installations provide to the country. This topic is in the sights of government officials. Due to routine training and testing activities that are significant ignition sources, wildfires are a constant concern on western continental military installations.

All land management organizations have started using quantitative computations to determine fire risk for locations for mitigation purposes. **The**

A.F. needs a quantitative way to evaluate the risk for ignition on installations and find ways to adapt to the challenge that climate change will bring. The A.F. works with the U.S. Forest Service to suppress wildfires with Mobility Air Fire Fighting Systems throughout the continental U.S. Pulling from the research done by the U.S. Forest service and international would decrease the time needed for personal research to be conducted by the A.F.

This thesis will generate a model for wildfire probability for multiple years to visualize a changing wildfire risk over time. The case study location, Vandenberg AFB, was chosen to facilitate a small-scale simulation in an installation that has been known to be affected by wildfires. Data required for the chosen location include elevation, slopes, aspects, canopy covers, canopy heights, crown base height, and crown bulk density [Finney, M. A. 2006]. Much of this data is available in a spatial data format compatible with GIS. The weather data was gathered from the weather station on Vandenberg AFB. The software programs, ARCFuels, ArcMap, Fire Family Plus, and FlamMap, are the basis for building and displaying the burn probability models. Burn probability models will facilitate risk management options for the Air Force. The output will allow forecasting the changing threat based on climate change, pending data availability. This study will generate a framework. Spatial, quantitative characterization of wildfire risk would allow identifying areas on the landscape where aggressive treatment might be cost-effective or where fire may play a

benign role. With minor alteration, this can be expanded to be utilized A.F. wide as a decision factor.

The Growth of Simulation Usage

Land managers are tasked with understanding the wildfire risk of the location as well as ways to mitigate and suppress the situation. An essential aspect of that has become modeling the fire behavior of their area to have a quantitative assessment of wildfire risk. Previous researchers utilized modeling to map fire behavior and forest management suitability [Ager, Alan A. et. al 2019]. The authors used the information to build a prototype investment prioritization framework that targets highly exposed communities where management activities would be cost-effective [Ager, Alan A. et. al 2019]. Wildfire modeling uses the components discussed earlier in some formulas to simulate the spatial and temporal spread for potential fire growth.

In the past, the U.S. Forest Service put forward a large-scale computer simulation model called FOCUS without a complete understanding of the mathematical interrelationships between the variables. This was a deterministic model with stochastic aspects. FOCUS used historical fires as a start base and estimated the distribution based on spread rate in fuel conditions [Bratten, Frederick W. et. al 1981].

In today's age, the high computational ability of computers has allowed simulation using the multiple variables that make up a wildfire. Topography data

can be pulled from various sources such as GIS, satellite imagery, and lidar. Weather for a location is usually open to the public and can be found at the nearest weather station online. Vegetation composition traditionally discussed as the "fuel" can sometimes be challenging to find. Many land managers are on-site after location surveys.

The U.S. has generated multiple systems that simulate wildfire as ongoing research into ignition risks. The USDA uses the programs behave, flam map, and fire simulator, known as fsim, fire family plus, burn Pro, Fire cast, and others [Ager, Alan A. et. al 2019]. One of the most extensive systems used is the Wildland fire decision support system. This program can provide burn probability modeling exposure analysis that supports risk-informed incident decision-making [Finney, Mark A. et. al 2011]. U.S. model systems are based on the Rothermel fire spread model.

One of the strengths of the usage of fire modeling of this computational style is how adaptable the outputs are to find the wildfire risk to an object or people instead of just the land itself if the researcher wants to. In Mitsopoulos's journal, he assesses the risk of wildfire to the Urban landscape of Greece by spatially analyzing the area for the risk factors: burn probability, conditional flame length, fire size, and source-sink ratio (SSR) [Mitsopoulos, I. et. al 2015]. FlamMap and ArcFuels were used with GIS residential structure mapping to generate the factors visually using three scenarios: extreme, moderate, and low

[Mitsopoulos, I. et. al 2015]. The journal shows a visual fragility curve of how the Urban area is at risk by wildfire by doing three methods. Another journal focused on finding the wildfire risk to oil facilities [Khakzad et. al 2018]. This was done modeling the fire behavior in the Solid Flame Model. The versatility of the model used depends on the user.

Organization of Chapters

In this paper, the programs ArcGIS, LANDFIRE, and FlamMap generate a fire probability model for Vandenberg Air Force Base to assess how climate change has affected the installation. This chapter will be followed by a literature review that will discuss current literature and the functional structures of the thesis. The literature review will be followed by a methodologies section detailing what programs were used, how data was gathered, how data was structured, and the creation of the outputs for this thesis. After the method section, there will be a discussion portion that displays findings from the model outputs. The final section of the paper will be a conclusion to the research done.

II. Literature Review

Summary

The purpose of this chapter is to provide a review encompassing past research relevant to the subject. The chapter provides a breakdown of the drivers that affect wildfire ignition and spread. Following the wildfire drivers is a discussion on fire modeling. The discussion will include who uses fire modeling, what has been done, what is used now, and what benefits land managers gain. Following is a review of the effect climate change has had on wildfire drivers.

Wildfire Drivers

The wildfires are a natural weather event that causes damage to its surroundings. These types of events have affected locations throughout the world for millions of years. Humanity has researched this phenomenon to understand and suppress these occasions. The first step in creating a wildfire is to break down components. Research on this subject showed how they spread, ignite, and the essential items that lead to a wildfire.

After wildfire has ignited, it spreads spatially in three types of ways, crown, surface, or ground [National Geographic Society 2019]. These three types of forms can happen at the same time or even because of another. The first type of wildfire is known as crown wildfire. This wildfire spreads through the canopies of

trees High above the ground. Crown wildfire spreads from its ignition point by lighting the leaves of trees in flowing across multiple trees [National Geographic Society 2019]. They are most effective in areas with a high density of trees. Another way that Wildfire spread is through surface wildfires. Now, surface wildfires spread along the ground. This type of wildfire originates in open fields among dry grass and shrubs [National Geographic Society 2019]. Because of the open area, surface wildfires are known to spread the quickest and are hard to suppress. The final type of wildfire is called a ground fire. Ground fires burn roots side of the ground [National Geographic Society 2019]. Ground fire is one of the hardest wildfires to notice and can lead to the continuation of surface wildfires by peeking back out of the ground and reigniting grass or shrubbery.

The following crucial component of a wildfire is the topography. Elevation and natural structures like Hills and valleys will affect the spread of wildfire [National Geographic Society 2019]. The other parts of the affected wildfire's topography are the natural vegetation any human interaction of a location. The first is the natural vegetation of the area. The vegetation on the site is the fuel for the wildfire to persist. Forest and shrubland have a different probability of burning compared to two more agricultural-like areas. Human interaction has a more significant effect on the vegetation and the chance of ignition. Wildland Urban Interface (WUI) is where urban settlements and wildland vegetation

intermingle, making interaction human activities and wildlife incredibly intense [Calvino-Cancela, Maria et al. 2016].

A southern Europe WUI study assessed fire ignition risk into areas burned and the interaction between land cover and land usage. Human population growth and land abandonment meant that mitigation actions needed to be altered for the current land usage. Calvino-Cancela looked at historical fires and broke the area into 14 classes of vegetation classified as either inside or outside of WUI areas [Calvino-Cancela, Maria et al. 2016]. The research affected WUI on the risk of fire ignition and spread ignition risk ran higher in WUI areas. The researchers found a noticeable pattern between land usage and if the area was in the WUI. The forests and the agricultural regions had the lowest ignition risk in comparison to other vegetation. This again shows the different type of vegetation has different likelihoods of ignition. The research also indicates that trouble lands generated larger fires outside of WUIs we're constant suppression, and mitigation actions were not taken [Calvino-Cancela, Maria et al. 2016]. A study from the Mediterranean found that, specifically, the probability of a large fire increased with distance to the Road while ignition probability decreased [Ager, Alan et al. 2014]. Human involvement is an interaction that does affect the likelihood of wildfire that requires more research.

The last factor that contributes to wildfire is the weather. Temperature, humidity, wind speed, and precipitation are factors that can Prime a location for

the extreme weather event. These variables have been recognized and used for what is called the fire weather index (FWI). The FWI is a weather estimated risk for a fire to ignite. This variable is also the most temporal as it changes throughout the year. This, in turn, means that fire risk varies as much as the weather does. The Mediterranean study shows an Eightfold increase in the odds of large fires on days with an FWI at 60 compared to any day or location with an FWI equal to 30 [Ager, Alan et al. 2014]. Their findings suggest that a relationship between FWI and Wildfire probability exists throughout the fire season. Seasons of the year have different weather variations. Some seasons get more rain. Other seasons are colder. It makes sense that the various weather seen in the seasons would affect if the location were likely to erupt into flames.

All these variables are meaningless, however, without taking account of the ignition methods for wildfire. A day with a high enough FWI and suitable vegetation could ignite a brush fire. A lightning strike is another common natural ignition source. Most ignition styles are man-made issues. In Sardinia and Corsica, history has found that more than 90% of historical fire ignitions were caused by negligence or arson [Ager, Alan et al. 2014]. Events like this have been seen in America when farmers or others burn fields as a part of their land-use practices and lose control.

Wildfire Modeling

As the computation power of computers has increased, the creation and utilization of wildfire behavior models to assess the risk of fire to civilization while focusing on different aspects have been rising. All quantitative wildfire risk assessment tends to be a product of a location's ignition probability and other or multiple variables. They require topological data for their location and branch from there for other data. Wildfire risk formulas are altered by each person based on what a person is focused on.

A study in southern Europe focused on how wildfire risk to the wildland-urban interface (WUI), the area in which civilization acts, is affected by the area's vegetation and possible wildfire ignition methods [Calviño-Cancela, María, et al 2016]. Historical fire data gave them 26,000 ignition points to pull a sample amount for a Monte Carlo simulation [Thompson, Matthew P., et al. 2015]. This generated fire probabilities throughout the land. The area's vegetation was broken into proportions denoting if it was in or outside of a WUI. The product of ignition probability and WUI proportion showed the fire risk of the area in use. This allowed the journal writers to review what vegetation is most likely to ignite. This method only uses topological data to generate the fire probability [Thompson, Matthew P., et al. 2015].

Different researchers expand on other variables using additional software to generate more precise risk probabilities. ArcMap and GIS have allowed for spatial-temporal models that account for more fire behavior variables than before. A wildfire risk estimation in the Mediterranean expanded on the utilization of historical fires seen in the previously discussed journal. ArcMap allowed the grouping of ignition points with Sardinia's nearest communities and roads using data from the Sardinian Geo Portal [Ager, Alan A., et al. 2014]. They used the computational power to create an ignition probability formula that incorporated land vegetation, daily wind speed, and daily temperature data from weather stations. The result was maps that land managers could use to target their fire detection efforts at the specific times of the year with high ignition probability and prioritize specific locations for mitigation efforts [Ager, Alan A., et al. 2014].

Many computational efforts are now being combined into program attachments to ArcMap to accelerate the ability to produce beneficial projects. This can be seen in the computation program named FireNVC [Thompson, Matthew P., et al. 2015]. It is a program that was developed to quantify and geospatially process the wildfire risk to highly valued resources and assets (HVRA). This program generates wildfire risk for each pixel of land as a product of the pixels' ignition probability and the net value of change of the benefits and losses caused by the fire. The research focused on the probability that an HVRA is

susceptible to burning and can even generate an output for the percentage of the HVRA that will be lost to fire [Thompson, Matthew P., et al. 2015].

Climate Change and Wildfires

With the weather being a high contributor to Wildfire likelihood, climate change is a factor in preparing wildfire risk and suppression. Climate change is there a long-term change of aquatic patterns on a global scale. Greenhouse gases and global warming in the atmosphere have been trapping radiation around the Earth. The trapped radiation has led to the atmosphere holding more water. The determined value of change in water-holding capacity of the atmosphere, governed by the Clausius–Clapeyron equation, has been found to be about 7% [Trenberth et. al (2003)]. As the mean climate of the world has warmed and atmospheric water vapor have increased, there has been a systematic decrease in subtropics precipitation with increases in land precipitation at higher altitudes [Trenberth 2011]. Issues caused by climate change are not going to end any time soon. The accumulated emissions generated by the greenhouse gases will take decades to diminish. The rate of change can be slowed, but it is unlikely to be stopped in the 21st century [Trenberth 2003].

Force management and human development have increased Wildfire incidents and risk but, climate change has exacerbated the trend of large fires and contributed to the lengthening of fire seasons into a year-round struggle [Phillips,

Carly 2019]. Fire regimes in the Europe, namely in Southern Mediterranean areas have been changing in the last decades, mainly due to land-use changes and climate driven factors such as increasing temperatures and extreme events such as droughts and heatwaves [Gouveia, Celia M. et. al 2016]. In the United States on the West Coast, climate change has caused hotter and drier seasons. This has led to a severe drought throughout the Western U. S. These droughts have caused less water to support our vegetation. Plants and trees are dying from the negative impacts of drought, such as hydraulic failure and insect infestation [Phillips, Carly 2019]. The insect infestation leads to dead and dry rotted trees. All of these factors create ideal conditions the fuel wildfire. The temperature change has led to fires erupting in December, now becoming a common issue. Earlier decades would not have worried about December fires because the vegetation would still be wet from Winter rain [Cart et. al 2019]. Other area with Mediterranean climates have similar drought issues. For instance, at the regional scale and at the seasonal or inter-annual time scales, severe droughts at the beginning of the fire season (late spring and early summer) inevitably lead to high levels of vegetation stress increasing the flammability of live and dead fuels [Parente, J. et. al 2019].

Wildfires are also worse than climate change by releasing large amounts of carbon into the atmosphere. Carbon traps heat in the atmosphere, which magnifies the heat around the world [Burke, Marshall et. al 2021]. This trapped heat also heats the land in elements with ice that melt the area [Burke, Marshall

et. al 2021]. The overall effect is a destructive cycle that causes more climate change, leading to stronger droughts and more wildfires.

These effects can be seen in the state of California. California is well known in the United States for its wildfire seasons. Michael Goss did a study to look at the weather's temporal change causing the increase in Autumn wildfires. The research looks at the FWI, temperature, precipitation, and area burned For All Seasons from 1979 to 2018 [Goss, Michael, et. al 2020]. The results showed an increasing trend in temperature, area burned, and FWI. Precipitation what's the only variable they had a negative direction. Further testing from the researchers showed that this trend would continue on the current course if environmental actions aren't taken to mitigate the issue.

Wildfire issues aggravated by climate change are having a monetary impact on California. The state burns through more than 4.7 billion between 2010 through 2019 to suppress fires instead of enacting mitigation efforts [Cart et. al 2019]. The state also creates a 21 billion compensation fund for the many victims throughout the California communities [Cart et. al 2019]. California currently does preventive power shutdown when conditions are windy and dry at a fire prevention measure.

Burn Probability

Burn probability and the ways it is generated has both strength and weakness. In simple terms, burn probability is the chance that a specific spatial location will burn based on certain components. Burn probability should not be confused with how fire occurrence has been used to generate burn conditions for areas. Fire occurrence uses historical data comparing fuel moisture with the circumstances over a large amount of land [Finney, Mark A. 2005]. Burn Probability is also not the Fire Risk; it is a crucial component to finding fire risk. Fire risk is found by multiplying the burn probability to a weighted score of the specific high-value resource wanted.

A simple and perhaps simplistic way to find burn probability is from taking historical data obtained from fire records that list the sizes or the mapped perimeters of fires that spread significantly [Finney, Mark A. 2005]. This way of generating burn probability is considered simplistic because of the result. The burn probability from the style states that the entire area has the same likelihood of burning. The earlier discussion about the vegetation component of wildfire showed how important the type of vegetation is to ignition. Computer computation has helped generate programs that can create more accurate models.

The Canadian system Burn-P3 is a good example. It is a landscape-level Monte Carlo simulation modeling approach. It is used, which combines deterministic fire growth modeling of individual fires with probabilistic fire ignition, spread event days (days of significant fires spread), and fire weather [Parisien, Marc-Andre et. al 2005]. The system combines a deterministic growth model probabilistic components of ignition with daily weather data to generate landscape-scale burn probability. This slightly differs from what Fire simulation (FSim) does. In general, FSim simulates weather, fire occurrence, growth, and suppression on large landscapes over thousands of simulations or fire seasons to estimate average burn probabilities [Parisien, Marc-Andre et. al 2020].

Burn probability maps are great for deciding what and where mitigation factors should be implemented. The maps can be used by fire managers to find the optimal locations for permanent lookout towers, create anchor points (i.e., areas where the construction of control lines start or end) for firefighter safety, locate areas of potentially limited suppression effectiveness (e.g., because of inaccessibility or scarcity of water sources), assess the risk in backfire or burnout operations (e.g., indirect attack), identify high priority areas for wildland-urban interface mitigation activities, and identify zones that require landscape-level fuels management [Parisien, Marc-Andre et. al 2005].

Limitations do exist when using burn probability. Due to burning probability computation using deterministic variables, the map results may not

be what has been seen historically. Burn probability is looking at every part of a location's fuel moistures and other variables at a grid level [Parisien, Marc-Andre et. al 2020]. Just because a location has the likelihood of burning does not mean that it has ignited or that it will ignite in the future. Burn probability means that the vegetation can ignite.

Another limitation is that the model is only a model. While it is reasonable to expect model outputs to reflect real-world fire activity, it is highly unreasonable to expect that the area burned by observed individual wildfires will constrain themselves to a particular range of burn probability values on the map: many wildfires (and huge ones) will burn across lands with a wide range of burn probability values [Parisien, Marc-Andre et. al 2020]. These burn probabilities are based on some deterministic values in a stochastic process that can not foresee everything.

The final limitation is the data quality. Burn-P3 and related models such FSim and FlamMap are susceptible to the quality of input data, such as the number and spatiotemporal patterns of ignitions, the accuracy of mapped fuels, and the care with which ignition frequency and fire size distributions are calibrated [Parisien, Marc-Andre et. al 2020]. If the input data that are off, then the map could skew to the wrong locations. Checking and verify that the data comes from trustworthy areas is essential.

Summary

The literature shows that wildfires are most affected by the location's topography, with the key component being the vegetation, the site's weather, how the fire is ignited, and what types of wildfires have ignited to spread spatially. These components have a high variability that requires high computational power to find the burn probability. This complexity is now possible with current-day computers. There are now multiple systems in both the U.S. and internationally that have methods of generating burn probability from given inputs of weather and topography. The wildfire variables are constantly changing due to weather. Climate change is causing changes to both topography and weather in the U.S. The drought and high temperature raise the probability of wildfire compared to previous years. As climate change continues, these weather actions, burn probability will continue to change. Finally, burn probability is great for many planning and mitigation actions towards wildfire. There are limits to the usefulness.

III. Chapter 3 Methods

There was a methodology to running the models in FlamMap. Figure 3 shows the steps taken to find burn probability of the case study location at different times. The first step was to gather weather and topographical information for the case study. From there a modeling system program was chosen that fit my modeling criteria. After this, the found data had to be formatted into the correct file types to be used with FlamMap. Then models were generated from FlamMap and exported for comparisons.

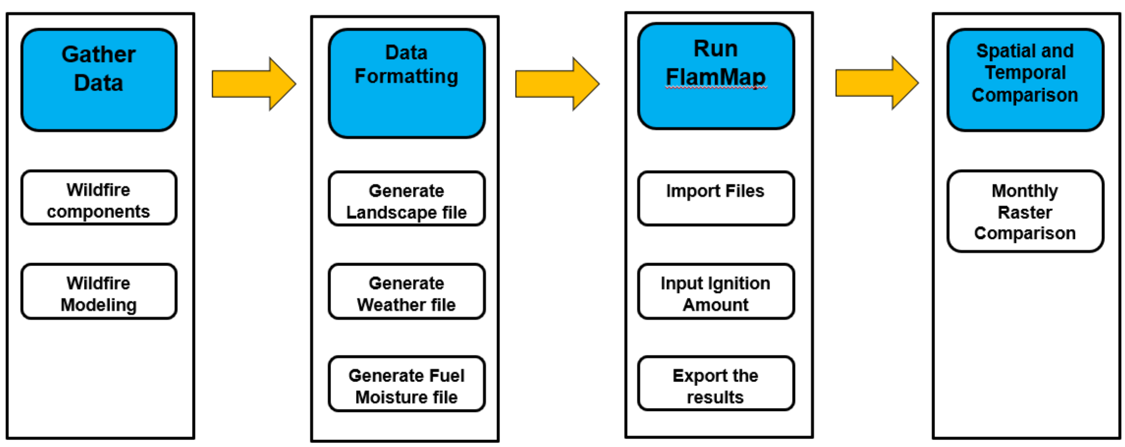


Figure 3-Methodology Workflow

Case Study

Vandenberg AFB is an installation located northwest of Lompoc, California. This location supports West Coast launch activities for the Air Force, Space Force, Department of Defense, National Aeronautics and Space Administration, national programs, and various private industry contractors. The climate of this area is similar to the Mediterranean. That area is filled with fire-prone weather situations such as long and dry summers with thunderstorms episodes, low relative humidity, and strong winds [Cadril et al. (2021)]. This means that southern California, like the Mediterranean, has been afflicted with drought, high winds, and multiple wildfires over the years made more intense by climate change [Cadril et al. (2021)]. The Canyon Wildfire at Vandenberg AFB, CA, in September 2016 burned over 10,000 acres and came close to two Space Launch Complexes. Incidents continued with a wildfire that grew to about 380 acres in 2017 and 140 acres lost in 2019. Based on these incidents, the base seemed a perfect location to model.

Selecting FlamMap

As discussed in earlier sections, many programs are used for wildfire simulations. The main challenge is picking which one to use based on the research that is to happen. For this thesis, the program FlamMap was the primary program utilized. FlamMap is a fire behavior simulator developed by the

USDA to map a static fire behavior representation across the desired location. FlamMap uses calculation on the pixel level of the landscape. It uses vegetation, crown stand height, crown base height, crown bulk density, elevation, slope, aspect, humidity, precipitation, wind speed, and direction as they require input data for its calculations [Finney 2006].

This program was chosen for multiple reasons. FlamMap is a free and wildly used program throughout the United States for wildfire research. Its strength is modeling problem fires of extreme weather scenarios based on conditional inputs for land analysis. This type of analysis is perfect for looking at burn probabilities based on the weather conditions generated over monthly intervals. Using FlamMap for simulations requires understanding the physical factors that are the needed inputs to affect wildfire intensity modeling. These factors are the land's topography, the weather conditions of the land, and the fuel scape that covers the land.

Topography

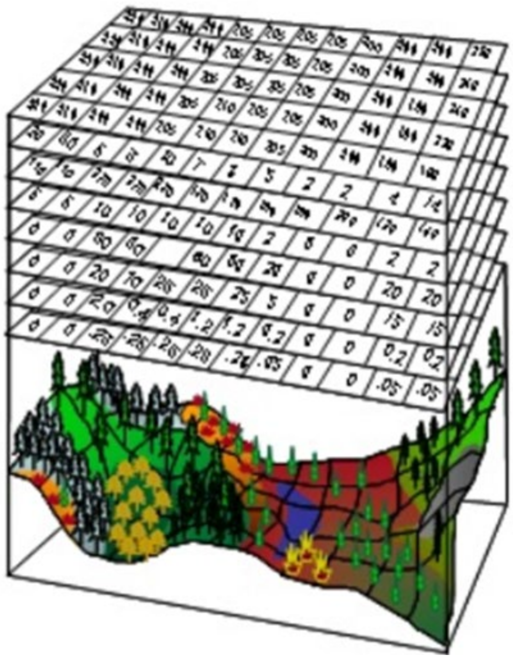


Figure 4-Landscape File (LCP) schematic from Finney, Mark A. (2006)

For the topography of an area in FlamMap to work, the data must be inputted as a Landscape (LCP) File. A Landscape File is a binary file comprised of a header and a body of short integers for each of the themes it contains [Finney 2006]. The header contains information on the bounds of the area, the resolution of the cells, and the units of the themes. An optional Projection (.PRJ) File may be present in the same folder [Finney 2006]. This LCP file requires eight rasters to function. These can be seen in figure 4 above. Another caveat is that all the

themes are raster files that must be in a 30m x 30m resolution with identical extents and use the spatial reference of 1983 NAD Aders [Finney 2006].

ArcMap is a tool developed by the creators of ArcGIS that represents geographic information as a collection of layers and other elements in a map. Common map elements include the data frame containing map layers for a given extent plus a scale bar, north arrow, title, descriptive text, a symbol legend, and other components. Breaking the information down into those separate layers allows the user to edit the data sets and implement multiple geoprocessing actions to calculate variables. The alterations done to the data can be turned into a visual map representation. ArcMap gave the ability to create the rasters needed.

The LFDAT gave the required data resolution and extent for the case study area. The LANDFIRE Data Access Tool (LFDAT) held the topographical data needed for the case study. LFDAT is a tool developed utilizing the LANDFIRE Project, a partnership between the wildland fire management programs of the U.S. Department of Agriculture (USDA) Forest Service (F.S.) and the U.S. Department of the Interior (DOI) to generate a complete nationally consistent collection of more than 25 geospatial layers (e.g., vegetation, fuel, disturbance, etc.), databases, and ecological models [USDA 2021]. This tool is an ArcGIS toolbar that gives direct access to the LANDFIRE Database that allows a user to extract raster files and the desired extent of the study and merge them into the needed Landscape file (LCP) used in fire behavior analysis simulators. The

LANDFIRE Project's detailed geospatial mapping products have become a critical component of wildfire behavior analysis for this thesis.

Weather Conditions

The original obtained weather records from the supervisor contained data for Vandenberg AFB from 1985 through 2019. This data was great to look at the historical trends of the case study. Sadly, the weather data could not be used directly in the model. Instead, it was used to compare the actual data used as verification of similar outcomes for the dates. Weather data used in FlamMap is formatted as a weather stream file (WXS).

This file has the data broken down to the date, temperature, relative humidity, precipitation, wind speed, wind direction, and cloud cover broken down into hourly data. Due to formatting requirements, data from the remote automated weather station (RAWS) was pulled from the installation using their weather station code. The data was then checked against Vandenberg records as verification. Errors and large amounts of missing data were found throughout the data until 2003. The data from RAWS comes in a format that cannot be used in FlamMap. The daily information must be expanded into an hourly weather stream file format that can have no more than a three-hour break between data [Finney 2006]. RAWS data can be converted into a WSX file through the fire family plus (FF+) program.

FF+ is a software package used to calculate fuel moistures and indices from the U.S. National Fire Danger Rating System (NFDRS) using hourly or daily fire weather observations primarily from Remote Automated Weather Stations (RAWS). This tool is constantly improved by developers of the U.S. National Fire Danger Rating at the USFS, RMRS, Missoula Fire Sciences Laboratory in collaboration with developers from Altura Solutions to explore seasonal variations in fire danger and communicate conditions as they change throughout a fire season or from year-to-year.

A WSX file was created for each month from 2003 to 2017. All breaks more than three hours were filled with the previous hours' data to compensate for the missing information of the weather data. If a single or multiple days were missing, the previous day's data was inputted to fill the gap. The total time taken to review and fill out the corrections for the 51 months used for the thesis was clocked at 60 hours.

Fuel Conditions

Fuel includes live fuel and dead fuel (ex. Forest floor, shrubbery, needles, grass, and shrubbery mixed with litter, etc.) play a critical role in the potential for a location to become ablaze. The LFDAT contained the fuel model data at the 30m x 30m resolution and extent required for FlamMap usage. The data

contained in the fuel model help to generate the two primary fuel models used in America, Anderson's 13 Fire behavior fuel models (FBFM13) and Scott and Burgan's 40 Fire Behavior Fuel Models (FBFM40) [Scott et. al 2005]. The models for this thesis used FBFM40. FBFM40 fuel model expanded on FBFM13 and gave a more precise rating for each fuel type [Scott et. al 2005].

This data is converted into an Initial Fuel Moistures File for FlamMap. The Initial Fuel Moistures (.FMS) File is an ASCII text file required for any FlamMap run. It requires the Fuel model number based on either FBFM13 or FBFM40 that describes the fuel type, the 1-, 10-, and 100-hour moisture content percentage of dead material, and the percentage of live wood and live herb content of the fuel.

To create the FMS file, we had to open the FBFM40 raster file in the GIS program, ArcMap. Using the raster to polygon tool produced a shapefile with the needed labels for fuel types. This shapefile was then clipped using the clip tool by a shapefile of Vandenberg Air Force Base made by clipping it from a shapefile of all CONUS Air Force Bases to give us the fuel types only in the base itself. After gaining the fuel types, the “Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel’s Surface Fire Spread Model” was used to determine the moisture content for the location. The category D3 was chosen for the intensity of the 1-,10, and 100-hour moisture content due to the drought trend in California.

Running Simulations

With the data now formatted for FlamMap, it was time to use the program to find the burn probabilities. 2003, 2009, and 2017 were chosen to be run for all of their months to see how burn probability changed over time. The odd years from 2003 to 2017 had the months July, August, and September modeled to see any trends in burn probability. All month models were run in FlamMap using to find their burn probabilities. FlamMap produces a single output map that contains the fraction of the number of fires that encountered each cell (0.0 to 1.0). On the first page of a run, the conditional factors are inputted. File inputs cover most factors with primary data followed. Humidity was input into the general section at 100 percent. In the step-through guide, the humidity was recommended to be kept between 100 to 130 percent if using the general section, with 100 percent representing drought conditions in the summer. The wind was also input into the general section. The wind speed chosen for the models was 28 miles per hour. This was the max speed found for the area during the summer months for 2000 and 2019. The last part is picking the hour and dates for the weather stream file to condition the area's fuel.

A burn probability model is accomplished on the third tab that looks at the minimum travel time of the flames based on the information given on the first tab. The models of this thesis had 1000 spontaneous ignitions. This was done to

thoroughly saturate the case study area to understand better what may ignite. All models also had a run time of 480 minutes to simulate a two-day fire with a four-hour-per-day burning period. The run time of each model ranged from 20 to 30 minutes to calculate the burn probabilities based on the provided conditions. The result generated is a raster file containing a burn probability for each pixel of the LCP file. The total run time for all models was found to be estimated at 1,530 hours.

These raster files were then exported from FlamMap as GeoTiff files for usage in the coding program known as R. In R; the GeoTiff rasters were converted into arrays containing the data of burn probability. This allowed the mean of burn probability to be found from every pixel generated from the raster.

IV. Results and Discussion

Vandenberg's historical data in figure 5 shows an odd trend of decreasing max temperatures. Minimum temperatures increase was expected as an aspect of climate change. The trends for both max and min temperatures of the historical model were found to be insignificant due to the high p-values found. Figure 6 focuses in on the area of time that the thesis generated models for. The maximum and minimum temperatures for the years follows the overall trend seen in the historical data of figure 5. The mean burn probability for July through September shows a general gradual increase throughout the years. Though the data shows an overall upward trend, a shocking spike happens from 2007 to 2011 before leveling. Burn probability jumps from a .0004 percent chance of ignition up to a .002 probability.

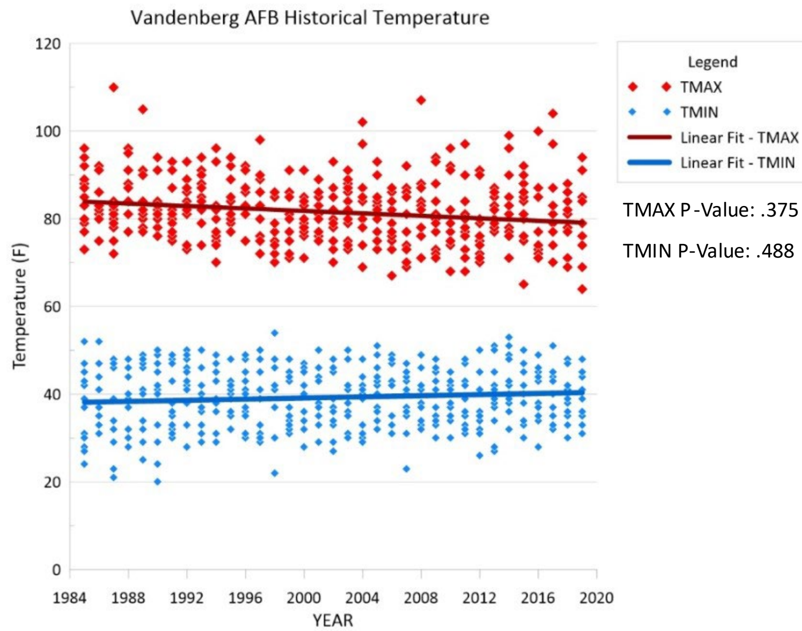


Figure 5-High and Low Temperature of Vandenberg AFB at a Monthly Scale

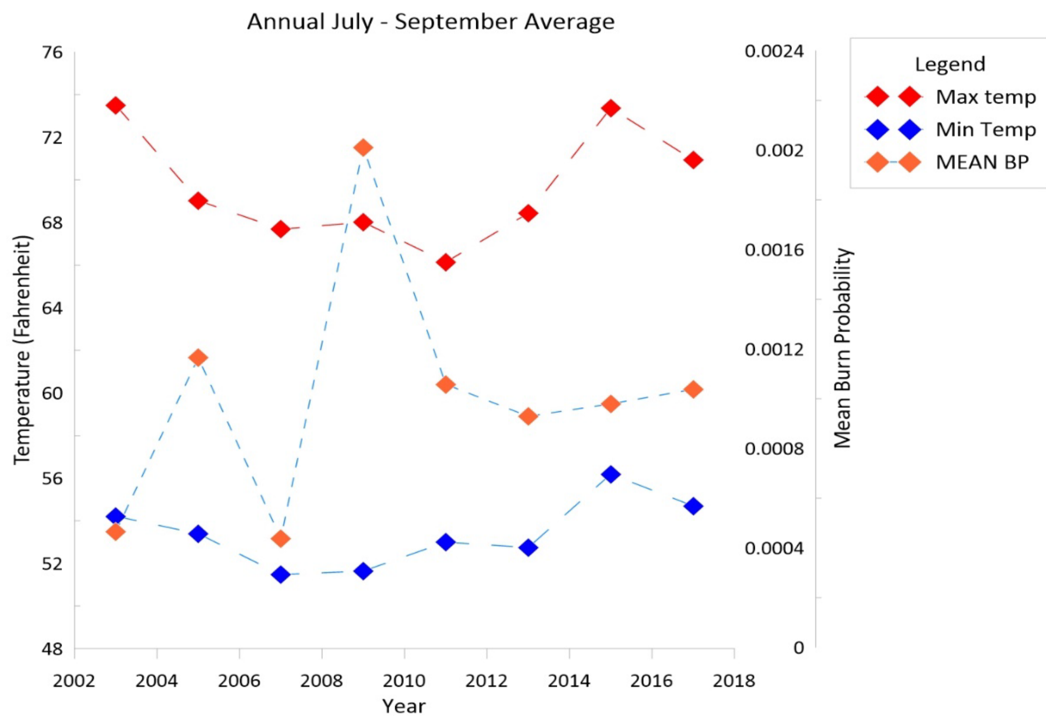


Figure 6- Burn Probability and Temperature from July to September

A closer look was done in figure 7 at 2003, 2009, and 2017 to better understand the changes over time to burn probabilities in Vandenberg AFB. All three expanded years have very similar seasonal patterns. Burn probability drops from January to February before climbing to peak ignition in April. 2003 and 2017 keep similar patterns to the increase and decreases to their burn probabilities, with 2003 overtaking the burn probability of 2009 and 2017 for December. 2009 was shown to be an anomaly that held the max burn probability of every month besides December.

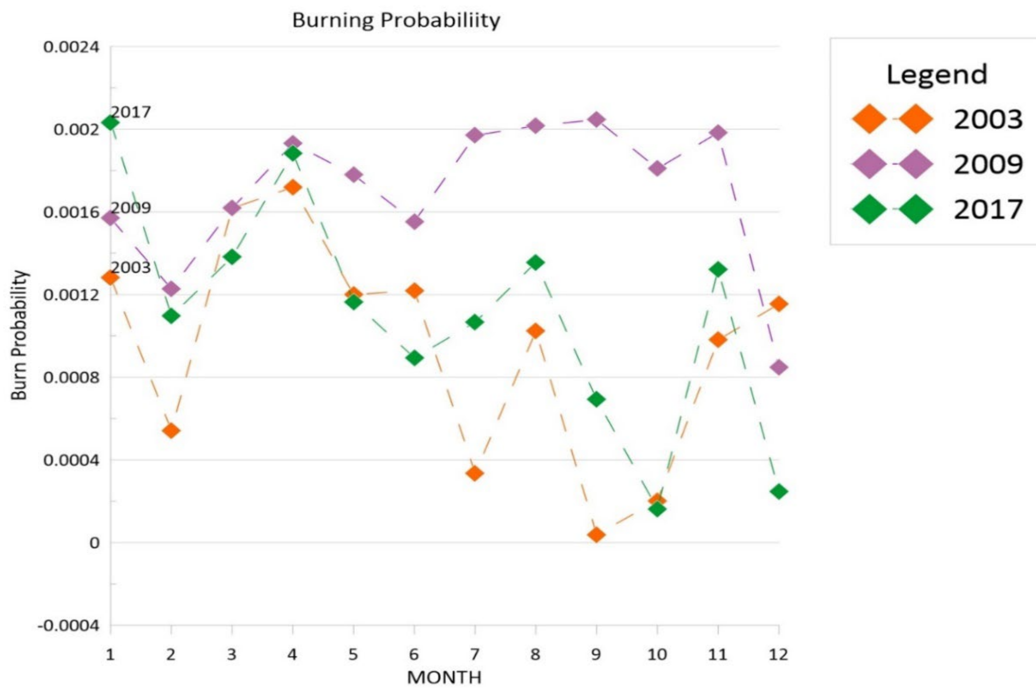


Figure 7-Burn Probability for 2003, 2009, and 2017

A closer look at the wildfire factors of all years was done to better understand what events may have attributed to the high burn probabilities of 2009. Two correlation tables were generated to compare the mean burn probability to the factors contributing to wildfires. Based on figure 8, temperature, both the max and minimum, negatively correlated to wildfire ignition. This seemed odd because it was believed that higher temperatures would positively correlate to having a wildfire ignite, with lower temperatures generating the opposite influence. Humidity and wind gust speed was found to correlate with burning probability positively.

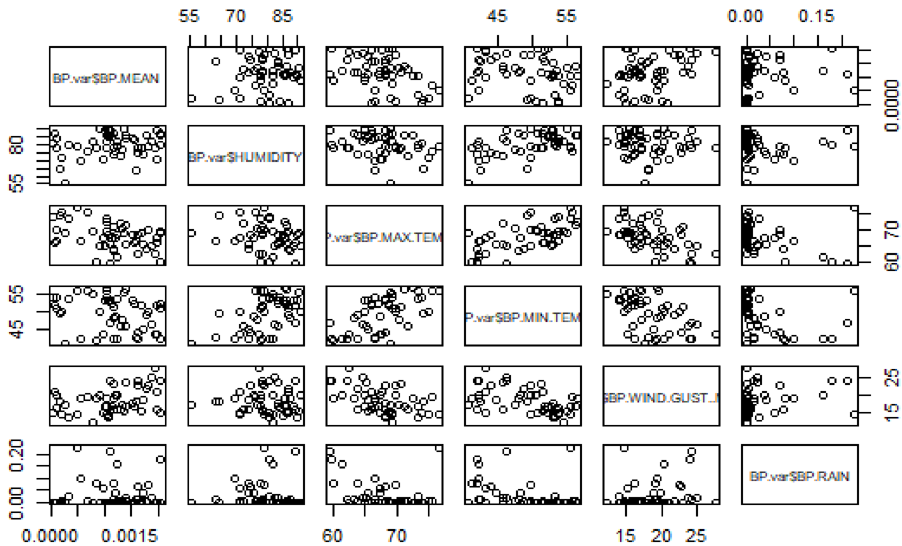


Figure 8- Graphical Correlation Table of Burn Probability Aspects

As stated in earlier parts of the thesis, one of the contributors to wildfire is the drought and wind that have been caused by climate change. Climate change has led to higher wind speeds that increase the chance for a wildfire to ignite. Due to climate change and green gas emissions, air can now hold more moisture and does not release precipitation as often as before. This effect has led to droughts throughout the Mediterranean area and California. Table 2 was done to have a clear answer compared to the graph formation of the first correlation table. The trends found in the previous figure were confirmed correct. The correlations, however, were not very strong for burn probability. The strongest correlation found for burn probability was max temperature with a -.41.

Table 2-Numerical Correlation Table of Burn Probability aspects

	BP.MEAN	HUMIDITY	BP.MAX.TEMP	BP.MIN.TEMP	BP.WIND.GUST..M.P.H.	BP.RAIN
BP.MEAN	1.00	0.21	-0.41	-0.24	0.34	0.02
HUMIDITY		1.00	-0.24	0.54	-0.05	-0.05
BP.MAX.TEMP			1.00	0.59	-0.50	-0.29
BP.MIN.TEMP				1.00	-0.51	-0.35
BP.WIND.GUST..M.P.H..					1.00	0.25
BP.RAIN						1.00

The found correlations believed to be tied to drought led to researching the level of drought through the years in California from the American website drought.gov. Looking at figure 9 below from drought.gov shows the standardized precipitation index (SPI) that is for California. SPI is an index used in the US to depict how drought affects a location is. The figure rates drought from abnormally dry (D0) to exceptional drought (D4). Starting at D2, fire seasons are expected to be longer and spatially spread farther than average. At D3, fire season is upgraded to a yearlong event that will affect certain wet areas of the state. It also shows the reverse of abnormally wet (W0) to exceptionally wet (W4). The year 2003 was a moderately wet (W1) one and 2017 was found to be a W4 year.

2009 was a year that was exceptionally dry with a D4 on SPI. It was also preceded by two years of D4. What is interesting is that 2017, despite being wetter than 2003, still had more months that had higher burn probabilities.

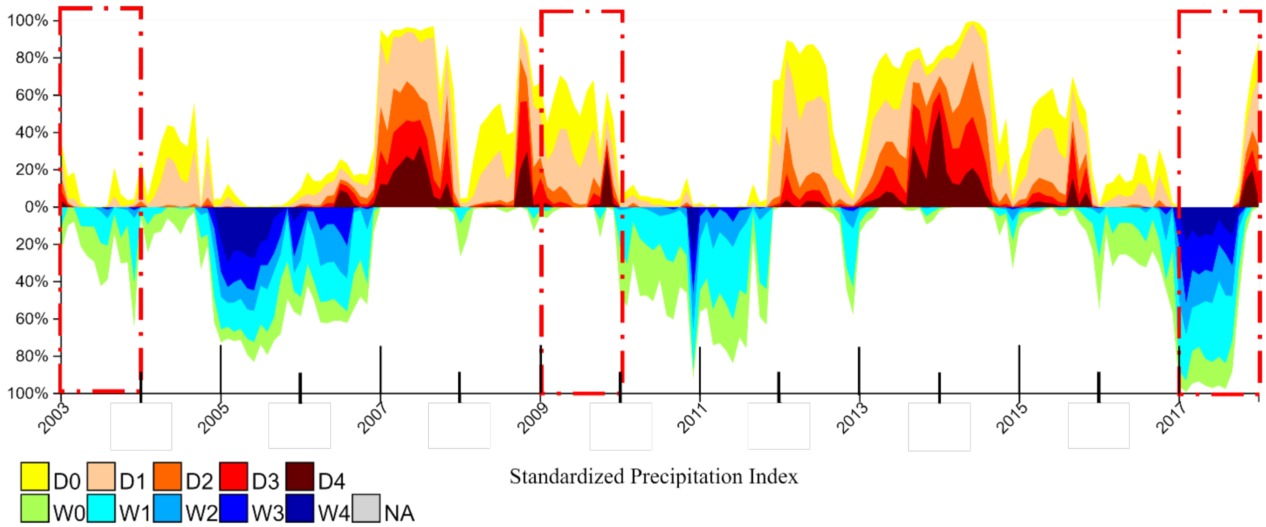


Figure 9- California Drought Standardized Precipitation Index generated by Drought.gov

This information means future issues for the mission at Vandenberg AFB. Vandenberg is used as a takeoff location for multiple space faring actions that generate extreme heat. The worry of wildfires is countered by current treatments of the surrounding areas, but the changing burn probability means increased danger from those moment of intense heat. These moments can even be exaggerated by a previous drought with how burn probability changes with non-stationary conditions and factors.

V. Conclusions

In summary, this thesis planned and outlined a possible pathway forward to develop a quantitative way to forecast the changing threat to installations based on climate change, pending data availability. The simulated burn probability demonstrated showed a general trend upward but showed inconsistency. 2009 burn probability beat out all years after it. This can partially be accounted for by the extreme drought. Drought does not explain inconsistency between 2003 and 2017. Going forward, future research should utilize forecasting of climate to understand what threat installations will face in the future. The DoD has started moving toward this goal with the creation of the Defense Climate Assessment Tool (DCAT). This tool, though still in the early stages of usage, was made with the goal of providing planning and land use recommendations through assessments to investigate mission impacts. The two future weather time periods of 2050 and 2085 would be beneficial for forecasting. Another step needed is the continual assessment of burn probability factors. This could be a bi-annual study done to keep track of the weather that is a non-stationary factor to the spatial spread of fire from an ignition. The final thought discovered in this thesis is that the Air Force needs to work closer with other on the forecasted wildfire threat. The Air Force currently works with the USDA and National Wildfire Coordinating Group (NWCG) when it comes to wildfire. For the Air

Force, the focus is on keeping the mission going by doing prescribed burning. These types of burning at firing ranges and other locations has worked up until now. Going forward this may no longer be enough. Instead of starting from scratch, working with other government agencies already working on wildfire should be done. A collaboration with the USDA, whose mission is the management of DoD land, in future wildfire studies would benefit the Air Force. The organization has already built programs for wildfire modeling.

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14. ABSTRACT

The intensity of extreme weather events, specifically wildfires, along the west coast has slowly grown over time due to atmospheric changes caused by climate change. The Air Force, though aware of the threat that is wildfire, does not currently have a quantitative way to assess the hazard to base locations. In this paper, burn probability is quantitatively calculated through the geospatial analysis programs to provide a means of assessing wildfire vulnerability.
The FlamMap fire simulator generated burn probabilities for Vandenberg Air Force Base using climate data generated by the remote automated weather station on the base to highlight how the burn probability has changed over time. The USGS data (Elevation, Vegetation,etc.) utilized in the model comes from the LANDFIRE Project. Results showed an increase in burn probability over time, but inconsistent overall trends. A closer look at the odd spike for the year 2009 showed that drought heavily impacted the burn probability. Further development of this framework should provide a valuable a tool to identify strategic plans for construction that align with land and missions resource objectives.

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