# It’s ‘Bout To Get Lit Up In Here

## Modeling Forest Fire Risks in Northern New Mexico

New Mexico
Supercomputing Challenge
Final Report
April 8, 2020


Team 59
New Mexico School for the Arts

Team Members:

- Rowan Jansens
- Madelyn Kingston
- Maya Landess
- Brandon Morrison

Teacher:

- Mohit Dubey

Project Mentor:

- Stephen Guerin

# Table of Contents

## 1. Executive Summary

Forest fires are unpredictable due to their ability to change their speed and direction at a moments notice, making it hard for emergency services to report and warn civilians if they are in danger. By knowing the initial starting point of a fire, the slope of the natural terrain, and the local wind speed and direction, the location and rate of the spread of forest fires can be predicted with greater certainty. Through research of previous forest fires and fire experiments, it is evident that slope has a profound effect on the rate of spread in a fire. By creating a physical fire model, we confirmed this effect and observed that fire spreads slower when going downhill and faster when going uphill. The slope vs. spread data we gathered in this physical model was crucial in developing an accurate computational model because we could base our calculations for the rate of fire spread off of observed real world data. We used a combination of this experimental data, agent-based modeling, and Geographic Information System (GIS) data to develop a comprehensive computational model of forest fires that accurately represent the effect that slope has on the spread of a fire in the Santa Fe area. We later explored and implemented the additional variables of wind speed and direction to account for changing weather conditions in the computer model as well as the amount of fuel in the modeled forest (density). By considering the wind conditions, density, and topography of a specific region using GIS data, the model is more predictive of fire spread in that specific geographical location. With this model, we can map the fireshed for Santa Fe which will provide valuable information about possible evacuation routes and the use of controlled burns to minimize risk.

## 2. Introduction

### a. Forest Fires

Forest fires are dangerous due to their unpredictable nature. Three factors that can cause variability in a fire's rate of spread are terrain, groundcover, and wind. The slope of a terrain can affect the speed of a fire, making it go faster or slower depending on whether the angle of the slope is positive or negative. Groundcover also has an effect on fire as the different possible arrangements and density patterns of trees can cause fire to burn in completely different ways. Wind can increase the danger of wildfires due to its ability to change the speed and direction of a fire very quickly. Historically, civilians living near areas where forest fires are more common have been put at greater risk due to a lack of access to evacuation alerts and relevant information during a fire. For example, during California's Camp Fire in 2018, a misjudgement of the fires location in combination with insufficient evacuation notices left thousands of people trapped on a highway surrounded by flames and at risk of being burned inside their cars (Arthur). This incident has made it clear just how important real time information can be in times of crisis. While first responders try to inform citizens as soon as possible about the safest evacuation routes and times, the unpredictable nature of wildfires can make this job difficult and often the information is not dispatched until it is too late. In New Mexico, two recent fires include the Las Conchas fire in 2011 and the Whitewater-Baldy fire in 2012. The Los Conchas fire burned over 150,000 acres of forest and infrastructure (Figure 1 left) and the Whitewater-Baldy fire burned over twice that (Figure 1 right). With an accurate fire model, it is not unlikely that these fires could have been extinguished more efficiently.

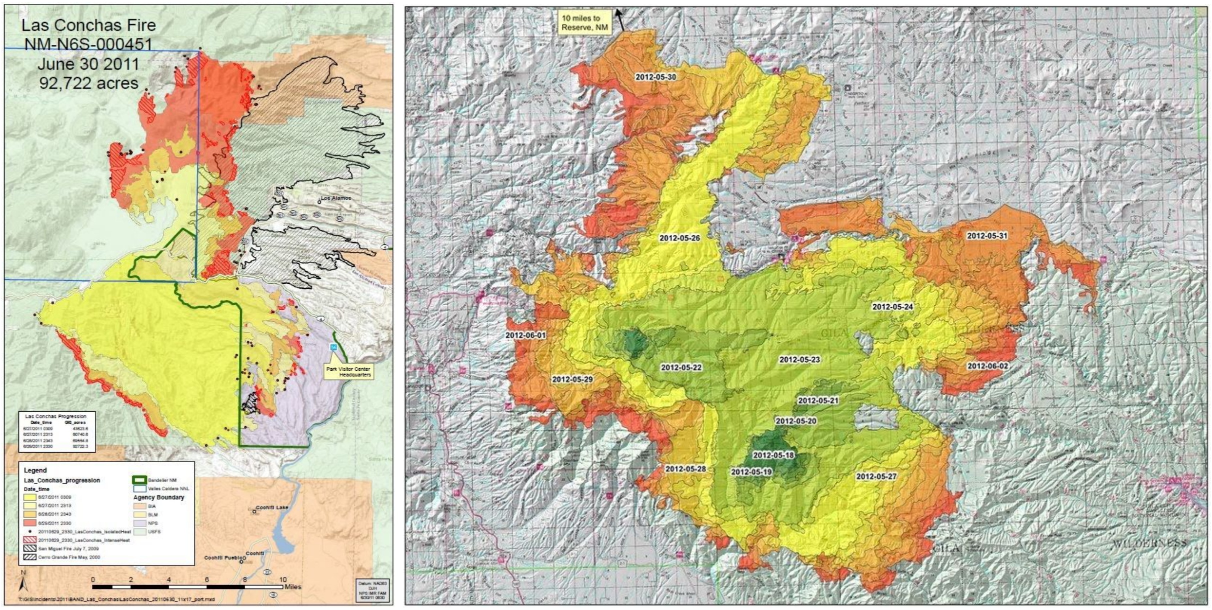


*Figure 1. The Las Conchas (left) and Whitewater-Baldy (right) fires were two of the most destructive forest fires in recent New Mexico history. These two maps show their path of destruction, including their starting points and how far they spread during their lifetimes.*

### b. Previous Approaches

When searching for past research done on this topic, we came across Richard C. Rothermel, who, in 1972, conducted several experiments measuring the effects of naturally occurring variables on wildfire, including slope. Rothermel had conducted experiments on slope in his lab where he burned fuel beds on slopes of 25, 50, and 75 degrees and then used this data to make his graphic model. (Rothermel) After reading his results, we set out to replicate and improve upon Rothermel's experiment and collect data to implement into a computer model.

## Slope Coefficient

The effect of slope was determined for fine fuels by burning excelsior fuel beds on slopes of 25, 50, and 75 percent. The experiments were conducted in a large combustion laboratory under the same environmental conditions used for the no-wind and wind tunnel fires. Fuel was excelsior constructed at four packing ratios: 0.005, 0.01, 0.02, and 0.04. A correlation of the data is shown in figure 22. The equation for the line is

$$\phi_s = 5.275\beta^{-.3}(\tan\ \phi)^2 \qquad (51)$$

where tan ϕ is the slope of the fuel bed. The final form of the rate of spread equation is

$$R = \frac{I_R\xi(1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}} . \qquad (52)$$

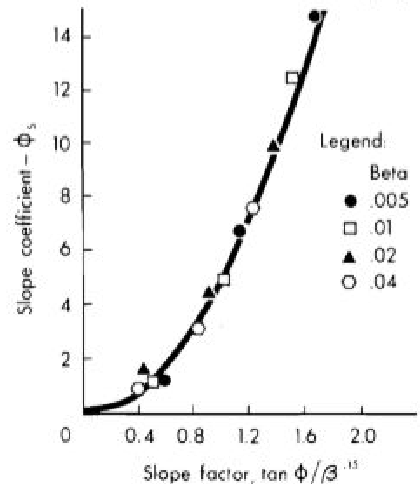


*Figure 22.--Correlation parameter for slope coefficient.*

24

*Figure 2. Richard C. Rothermel did studies on how different factors affect the speed of a fire. Here shows his work with slope, and the results he got from doing experiments with this factor*

Looking into how Rothermel designed his experiment, we identified several limitations. Notably, Rothermel had neglected to experiment with negative slopes and instead only measured the effects of positive slopes. By only considering a single direction of spread, Rothermel could not have gotten as comprehensive an understanding of the effect of slope on forest fires. While the scope of his experiment may have been limited, his procedure appears to be very thorough.

Since then, many researchers have used Rothermel’s research to aid further study into forest fires. In particular, Dr. Patricia Andrews looked closely at Rothermel's findings in addition to a number of other specific variables and used higher level math to compute their effects on fire (Figure 3).

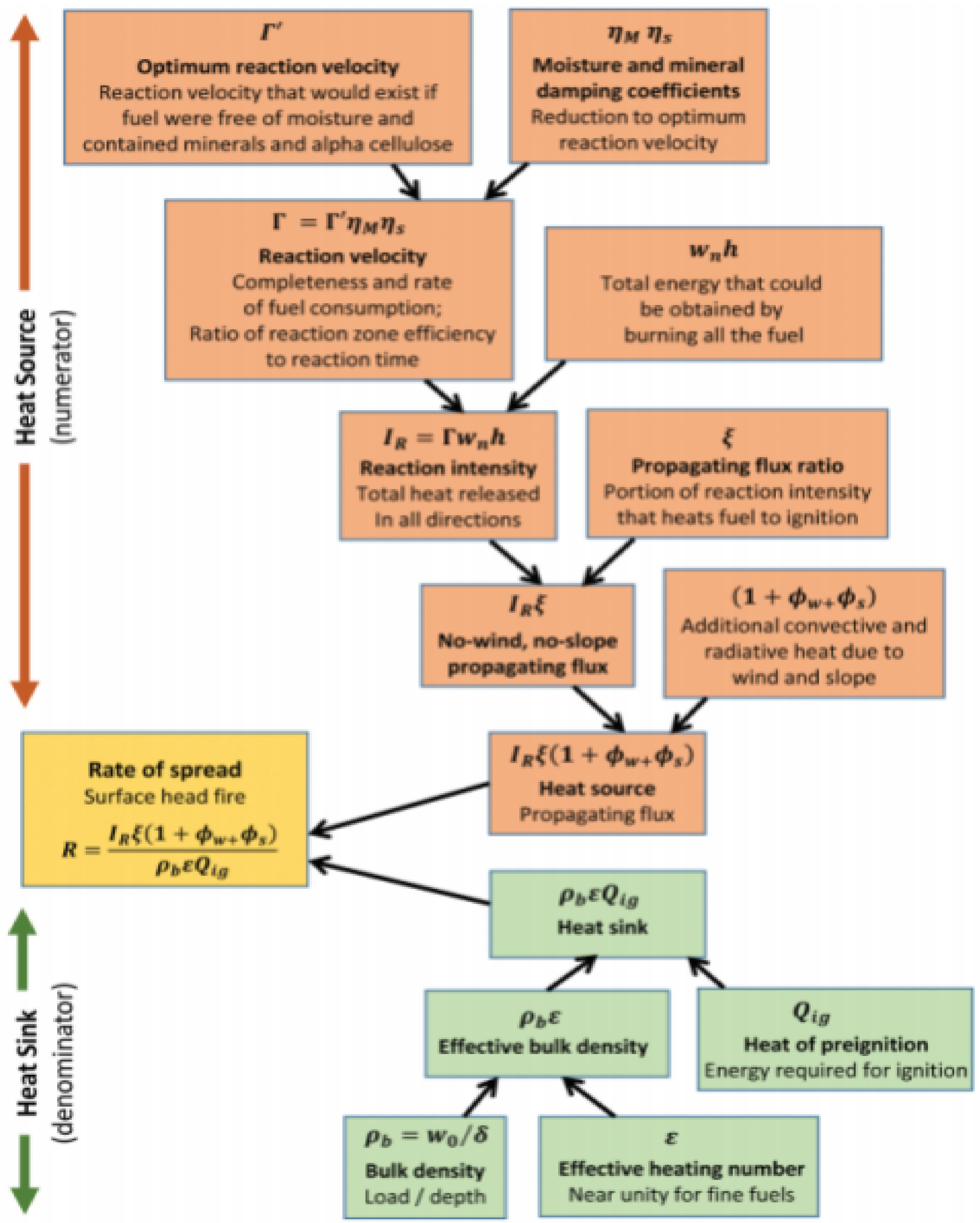


*Figure 3. Flow of calculations in Dr. Andrews' fire spread model for one size class of dead fuel. (Andrews, Patricia L.)*

While the mathematical depth of this research is incredibly comprehensive, the findings are not presented in simple enough terms to make the result useful to firefighters or civilians. In this project we hope to recreate some of the experiments carried out by these two scientists and use computer modeling to present our findings in a meaningful and useful way.

### c. Project Outline

The purpose of the project is to create an in depth computational model to be used to predict forest fire movement by taking into account three variables: terrain[1], groundcover[2], and wind. By doing this, we can create a tool to be used to help first responders combat a fire, provide the public with realistic fire locations and predictions during an emergency, help create efficient and safe evacuation routes for civilians, and identify current wildfire risks in Santa Fe. Although we will be investigating all three variables, the bulk of our work will be centred around the effects of the terrain as this seems the most misunderstood factor related to forest fires. In the following sections, we will discuss the process of implementing each of the chosen variables into the computational fire model and discuss how each new addition contributes to the model as a whole. We will also describe a series of parameter sweep experiments using the model as well as the results and their significance to our understanding of forest fires.

---

[1] While we will be referring to "terrain" through the paper, we are talking specifically about the inlince/angle/slope of the various hills and valleys that make up the topography of any given location.
[2] Ground cover refers to the placement and density of fuel (trees) in any given location.

## 3. Physical Model

### a. Motivation

To begin the project, we designed a physical experiment to study the effects of slope on the rate of fire spread. The overarching goal of the experiment was to develop an equation that could be used to calculate the burn rate of a fire when given an incline angle. This equation could then be implemented in the computer model allowing for a more realistic model of forest fires.

### b. Experimental Setup and Procedure

We performed many preliminary tests to perfect the system and ensure creation of meaningful data. In the **physical model**[3], a sheet of A4 graphing paper is used to emulate a flammable plane similar to a forest. Through trial and error, we observed that the most reliable way to burn the paper was to elevate it off of any solid surface to allow for adequate airflow to the flames from both the top and bottom of the sheet. We used a metal mesh tray on which we could attach a sheet of paper on two rows of spikes on either side of the tray. The spikes hold the sheet of paper tightly throughout the burn. The tray isolates a 216 x 216 mm square target to study as the paper burns. The whole apparatus was set up in a fume hood and the vent was left <u>off</u> during the burns (Figure 4).

[3] Throughout the paper, the "physical model" will refer to the model described in this section where a sheet of paper is physically burned.

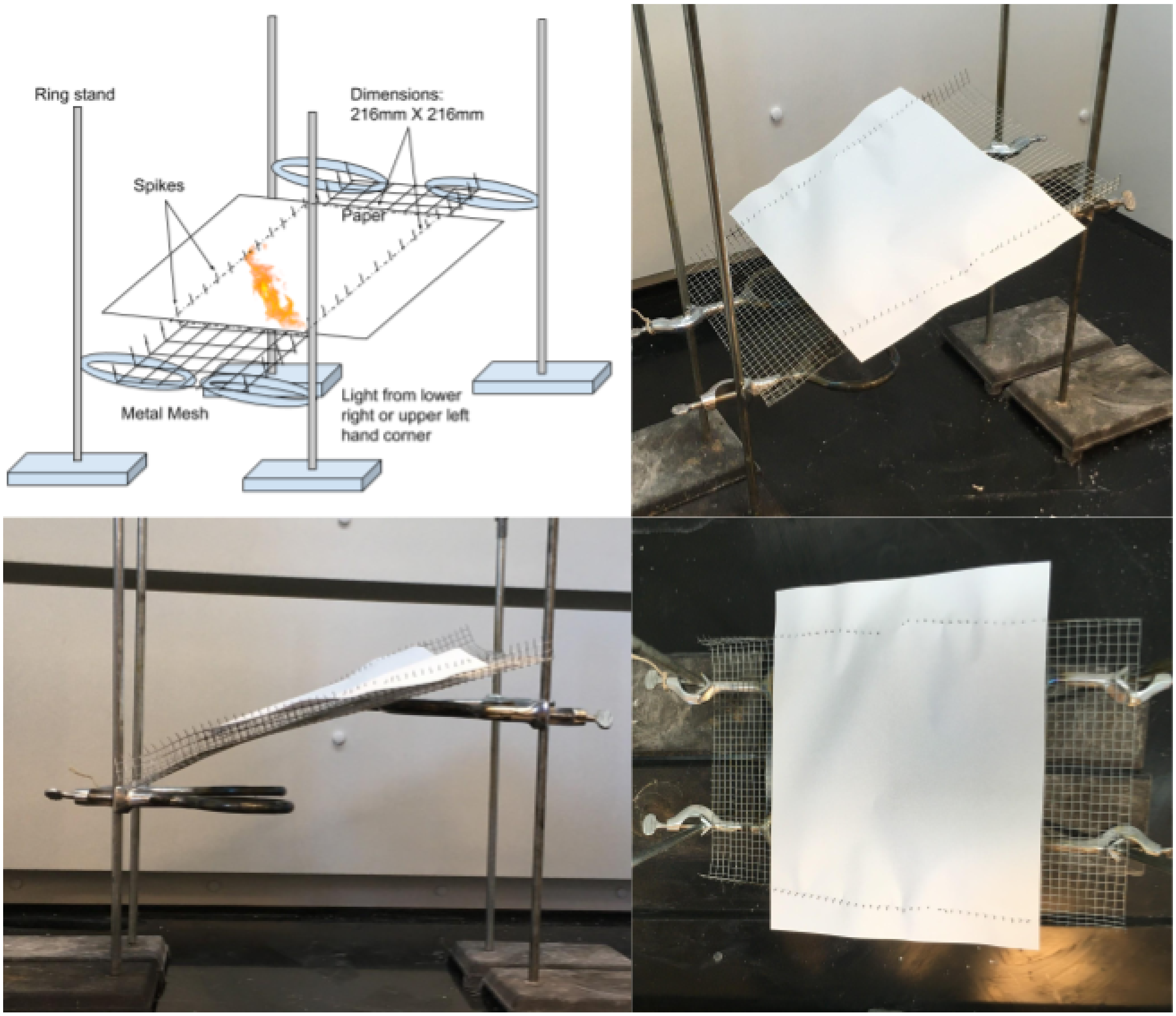


*Figure 4. Digital diagram of the physical model setup (top left), Corner View (top right), Side View (bottom left), Top View (bottom right),*

By changing the height of the four ring stands on which the tray rests, the incline of the paper can be adjusted to model sloped forest terrain. To measure and adjust the angle of the tray, we used the mobile "Measure" app on an iphone. Alternatively, a protractor could be used, however it is harder to get an accurate reading with this method as there are no accessible horizontal reference angles in the setup. We used a pocket lighter to ignite the paper in the lower right hand corner for uphill burns and the upper lefthand corner for downhill burns. During the burn, we took three time measurements: Up/Down (when the first flames have visibly reached the left or right of the page), Across (when the first flames have visibly reached the top or bottom of the page), and Total (when the whole paper has burned). It is important to remember that on uphill burns, the “Up/Down” time should be the shortest time recorded while in downhill burns, the “Across” time should be the shortest time recorded. We performed a minimum of three trials for the following 9 angles: -60°, -40°, -20°, -10°, 0°, 10°, 20°, 40°, and 60° and the data was recorded in a table.

### c. Data and Results

In order to better implement the results into our computer model, the data points need to be normalized by multiplying the recorded burn time (in seconds) by 0.463cs/mms. This represents the data in terms of an ignition delay time (in centiseconds per millimeter) which will allow the computational model to match the physical parameters of the physical model such as the paper’s dimensions and observed burn times. In the computer model, each tick will represent 1cs of time and each patch will represent 1$mm^2$ of the paper in the physical model. By graphing these normalized points along with its standard deviation and fitting the points using the IgorPRO software, a sigmoid function is generated that closely fits the “S” shaped curvature of the data points (Figure 5).

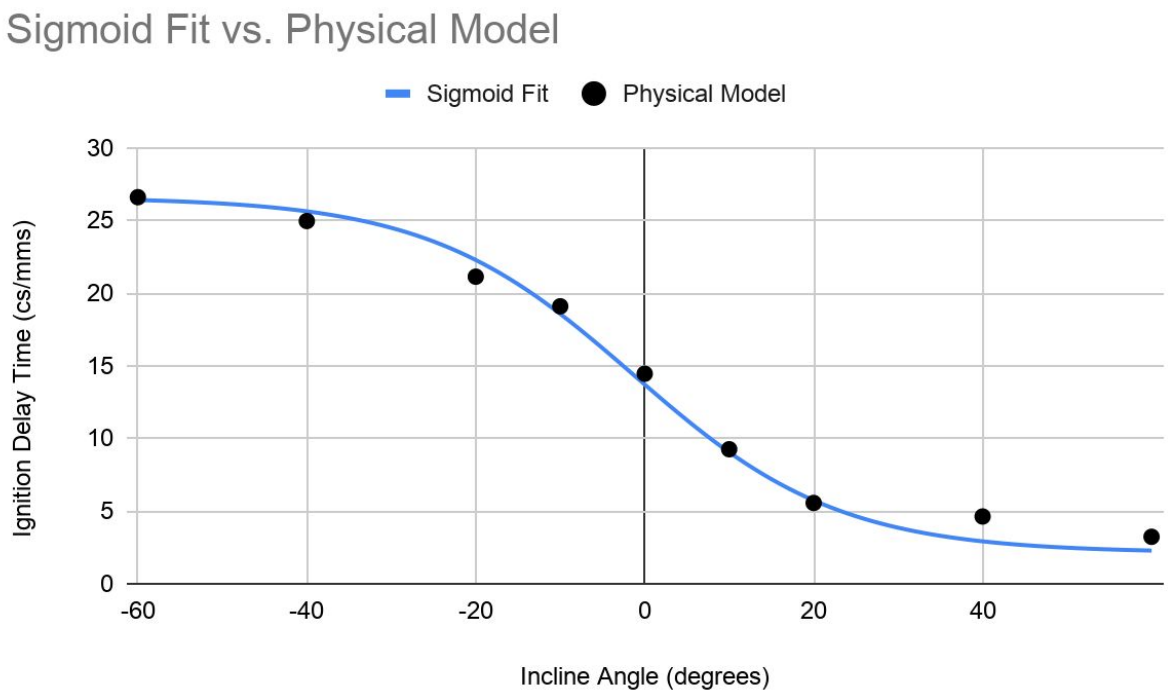


*Figure 5. The sigmoid fit plotted with the real data collected in the physical model.*

In the above graph, the sigmoid fit curve is represented by the function:

$$y = 26.596 + \frac{-24.465}{1 + e^{\frac{-1.296 - \Theta}{12.145}}}$$

where ϴ is the incline angle (in degrees) between two points on a plane and *y* is the ignition delay time (in cs per mm). This equation will be used in the computer model to calculate the time (in ticks) of delay before burning a target patch as a function of the angle between a patch and its neighbors computed using the patches' elevation.

## 4. Computational Model

### a. Slope Implementation

We chose to use the Netlogo modeling program to develop all of our fire models. The first model we created, referred to as the **basic computer model**[4], was designed to be a computational replica of the physical model. In the basic computer model, a square plane is created in the modeling program with dimensions of 216 patches by 216 patches. Because each patch represents 1 $mm^2$, the plane of the computer model and physical model are the same size. By selecting an incline angle, every patch is assigned an elevation to form a continuous incline along the entire plane. For example, a 0 degree incline will result in all patches having the same elevation while a 10 degree incline will result in a linear increase/decrease in elevation between columns of patches. This represents the uniform plane created in the physical model when the paper is angled using the ring stands.

To model the spread of fire, the angle between any two neighboring patches is calculated using a simple arctangent function. For the north, south, east, and west neighbors of a patch, the incline is the arctangent of the difference in elevation while for the northeast, northwest, southeast, and southwest patches, the incline is the arctangent of the difference in elevation divided by $\sqrt{2}$ (Figure 6).

---

[4] Throughout the paper, "the basic computer model" will refer to the computer model that recreates "the physical model".

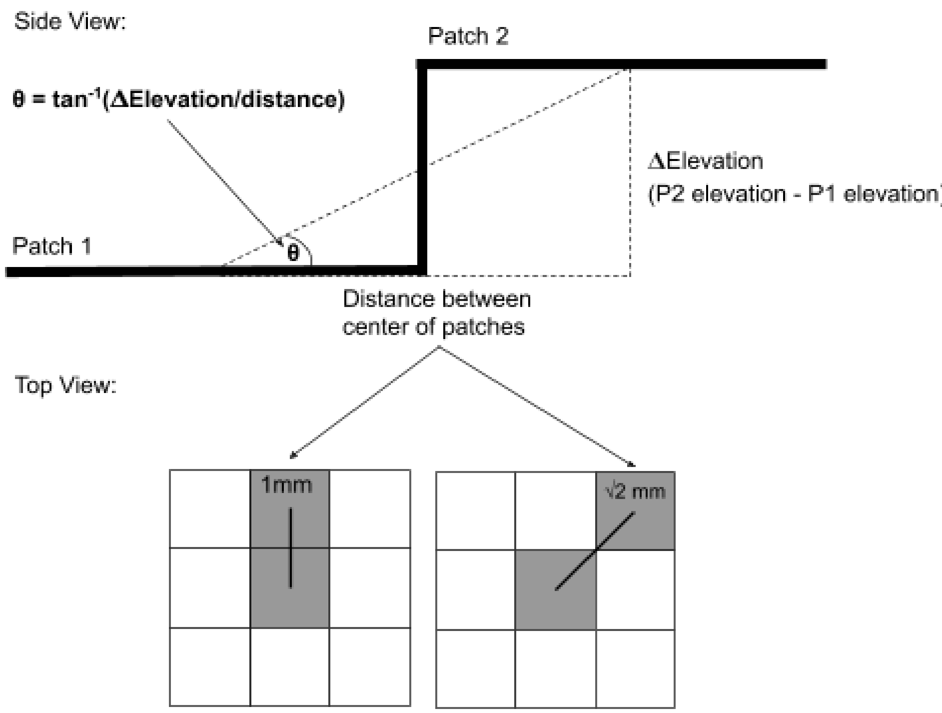


*Figure 6. A diagram showing how the "incline angle" is calculated for use in the function derived from the physical model*

Using the incline between a burning patch and its unburnt neighbors as an input to the equation derived in the physical model (Figure 5), an ignition delay time is created. The computer model then waits for the duration of the calculated delay for each patch after which the unburnt patches "catch fire". After the first loop, the new "burning" patches are then used to calculate the delay time for *their* neighbors.

Notes:

1. While in the real world, fires can spread in any direction, the computer model will be restricted to a fire spread in the 8 cardinal and intercardinal directions.
2. When two burning patches are competing to ignite a common neighbor, the code ensures that the shortest ignite delay will be used to ignite the patch. This is known as flood fill.

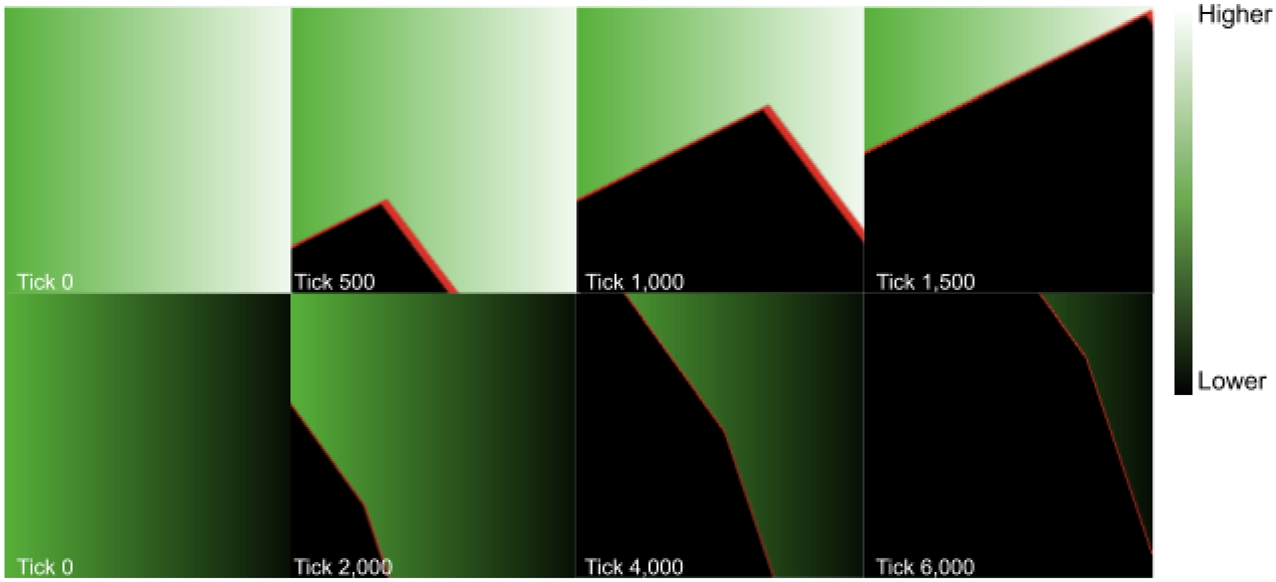


*Figure 7. Progression of the basic computer model completing uphill (top) and downhill (bottom) burns.*

While the up/down times between the basic computer model and the physical model are generally only off by ±4 second (Figure 8), the same cannot be said for the total time (Figure 9). While the general downward trend is observed in both models, the computer model consistently overcalculated the total burn time. This error likely results from the limitations of the model burning in only 8 directions. The Up/down time is only affected by the rate of spread in a single direction thus resulting in relatively high precision. The total time, however, is affected by fire spread in every direction and thus more susceptible to the limits of the model. Had the model been able to account for fire spread in a larger number of directions, the total time in the basic computer model would likely fall closer to the observed values in the physical model. While this model will be adequate to fulfill the further experiments, this slight inaccuracy should be kept in mind.

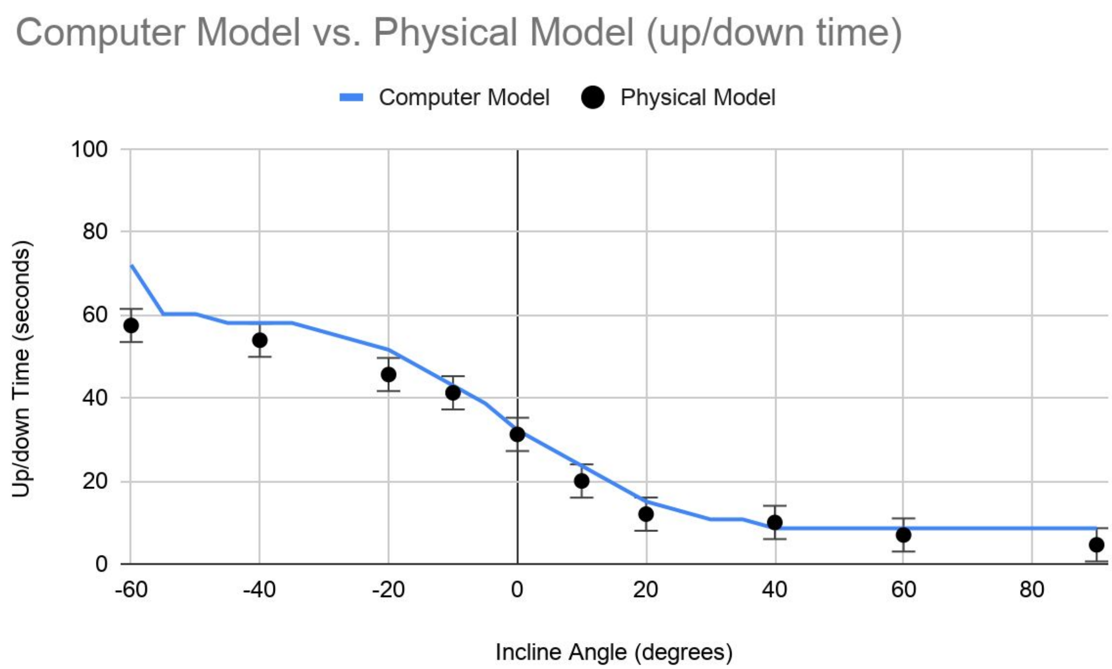


*Figure 8. A graph of the computer model's "up/down burn time" plotted with the comparable real data collected in the physical model. Error bars show ±4 seconds.*

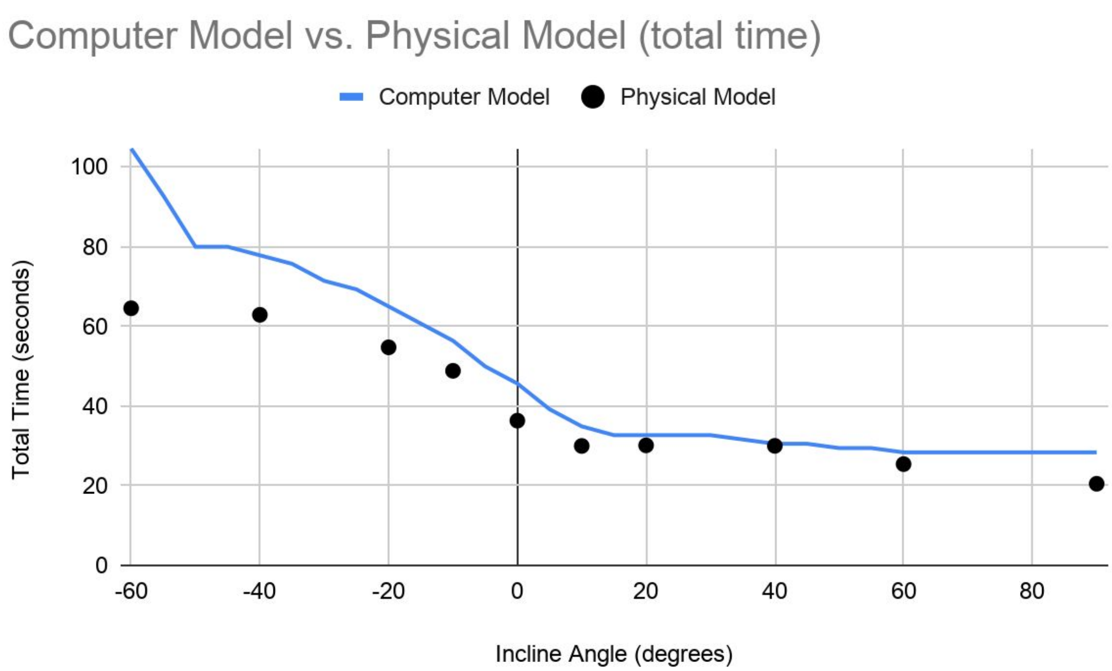


*Figure 9. A graph of the computer model's "total burn time" plotted with the comparable real data collected in the physical model.*

### b. GIS Implementation

Once the basic computer model had been refined and adjusted to match the observed behavior of the physical model, we introduced the real topography data for the eastern Santa Fe city and forest areas thrus creating what is known as the **GIS computer model**[5]. Alternate set-up functions were written into the code that assigned each patch in the plane a distinct elevation sourced from GIS data files. The GIS data was obtained from *the LANDFIRE program.* (Get Data) Elevation in the model is visually represented by a color gradient (Figure 10).

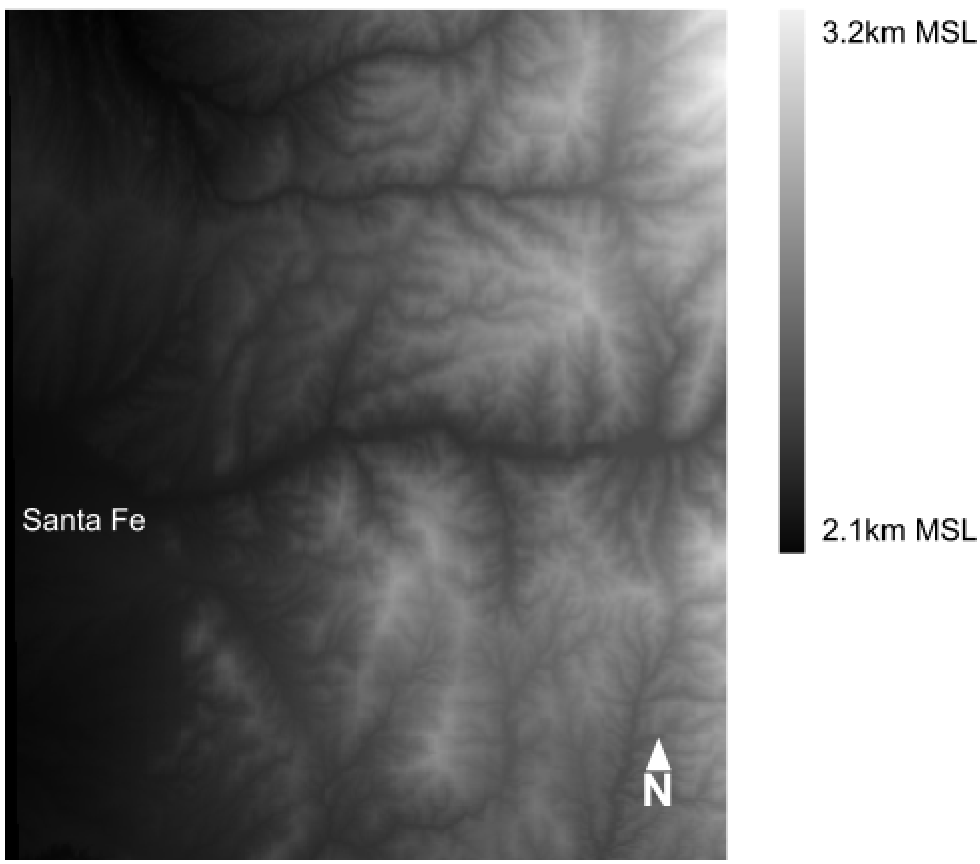


*Figure 10. Visual representation of the Santa Fe area using GIS elevation data in the computer model.*

[5] Throughout the paper, the "GIS computer model" will refer to the computer model that includes the GIS data for Santa Fe.

The arctangent function mentioned earlier is again used in the model to calculate the incline angle between every patch and its 8 neighbors. Then the incline angle is again used to calculate the ignition delay times throughout the burn. As expected, fires that originate at local maxima on the plane, such as on top of a mountain, spread less and result in a small fire due to the average negative incline slope. In contrast, fires that originate in a local minimum, such as in a valley, are more severe and burn a greater area of accelerated upward spread due to the average positive incline of slope (Figure 11).

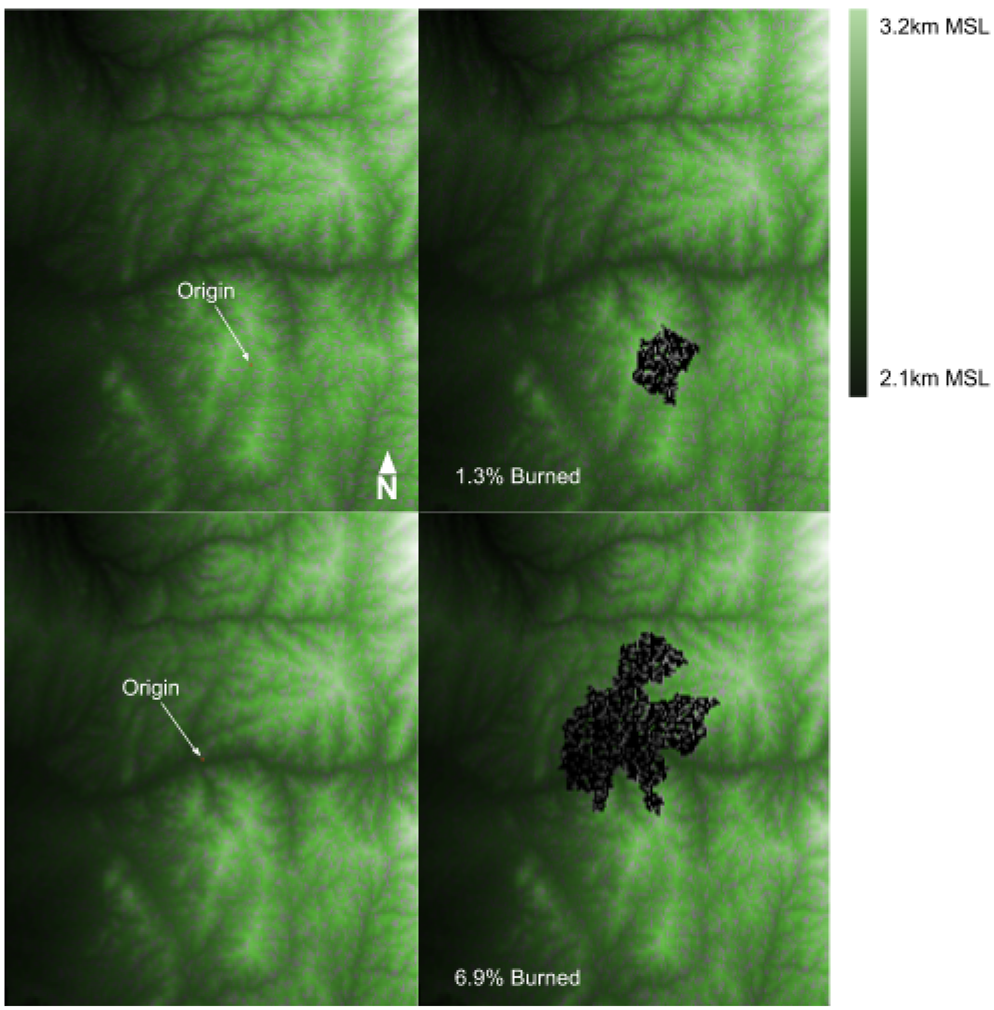


*Figure 11. The effects of fire origin on the size of fire in mountainous terrain.*

In addition to the GIS elevation data, we added GIS ground cover and fuel-type data to the model to show the real density and placement of trees in the Santa Fe area. Not only does this make the model more comprehensive, it also eliminates the inaccuracy of random tree placement across the plane. Flammability of patches is dictated by the GIS data and visually represented in the model by different colors (Figure 12). There are 13 fuel-types broken into four groups: grass, shrub, timber, and slash (Fuel Model). Shrubs and timber (types 4-10) are the most flammable and prevalent in the eastern Santa Fe area, so we limited our model to these types of fuels. Although all of the fuel types burn differently and spread at different speeds, due to time limitations, we were unable to incorporate this into our model. Instead, fuel-type and groundcover act as a boolean value making the patches either flammable or nonflammable. Adding GIS groundcover and fuel-type data enables the model to represent the current state of the Santa Fe area, making it ideal for aiding first responders in their efforts to fight a particular fire or locate safe evacuation routes for civilians in the case of a forest fire.

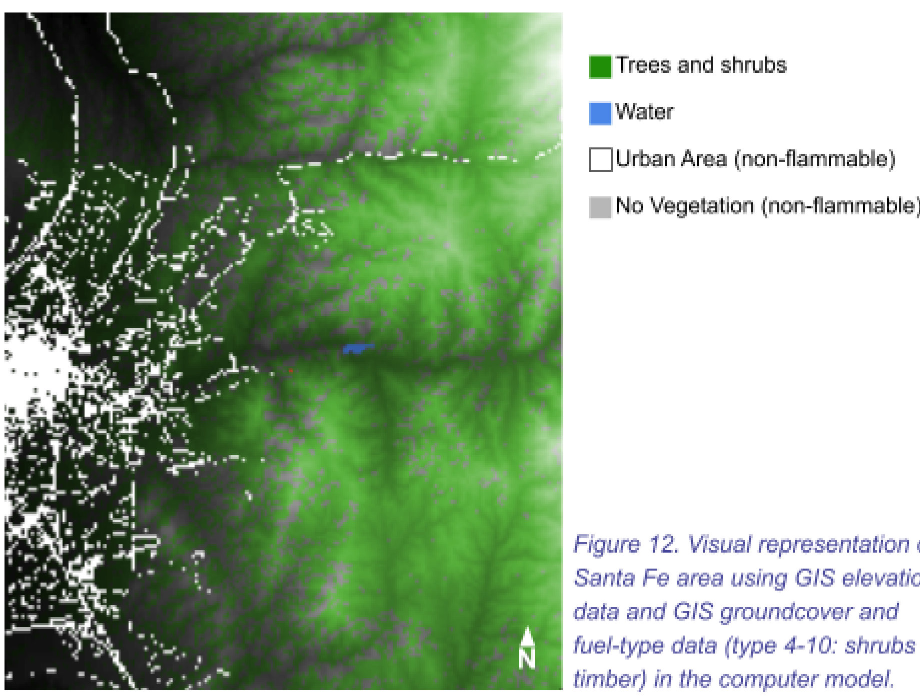


*Figure 12. Visual representation of the Santa Fe area using GIS elevation data and GIS groundcover and fuel-type data (type 4-10: shrubs and timber) in the computer model.*

### c. Wind Implementation

Another variable we intended to consider is the effect of wind on the rate of fire spread. At first we tried to modify our physical model using a fan to imitate wind in order to better understand its effect on fire. However, it quickly became clear that the sub-variables of wind such as its three dimensional direction vector and variable intensity quickly exceeded the practical limits of a physical model. Instead we went directly to a computer model with the acceptance that there would be some limits to its accuracy. Because the computer model already calculates the burn rate in all 8 directions for the 8 neighbors, it was practical to only look at 8 wind directions as well. With the understanding that wind in the direction of the fire spread will accelerate the rate of spread and wind against the spread of fire will decelerate the rate of spread, wind can be modeled by decreasing/increasing the ignition delay time in the computer model. After calculating the ignition delay for a particular patch, the computer model subtracts from it the cosine of the relative wind angle multiplied by the product of the wind strength and ignition delay. The relative wind angle is calculated by subtracting the fire direction from the wind direction. This effectively decreases or increases the ignition delay in proportion to the component vector of the wind. For example, assume a patch is going to ignite its northern neighbor (fire direction is north: 90° on the unit circle). If wind is also blowing north (90°), the relative wind angle between the fire spread and the wind direction is 0° (90° - 90°). Since the cosine of 0° is 1, the spread will experience the full accelerative force of the wind. If instead the wind is blowing northeast (45°), the relative wind angle is -45° (45° - 90°). The cosine of -45° is approximately 0.71 and so the fire in the northern direction will still feel an acceleration but not as strong as a parallel wind. Finally, if wind is blowing south in the opposite direction of the fire (270°), the relative wind angle is 180 (270° - 90°), the cosine of 180° is -1, and the fire will experience the full decelerative force of the wind resulting in a longer ignition delay in the northern direction. By applying this calculation to each of the 8 directions, the overall effect of wind on a fire can be observed (Figure 13).

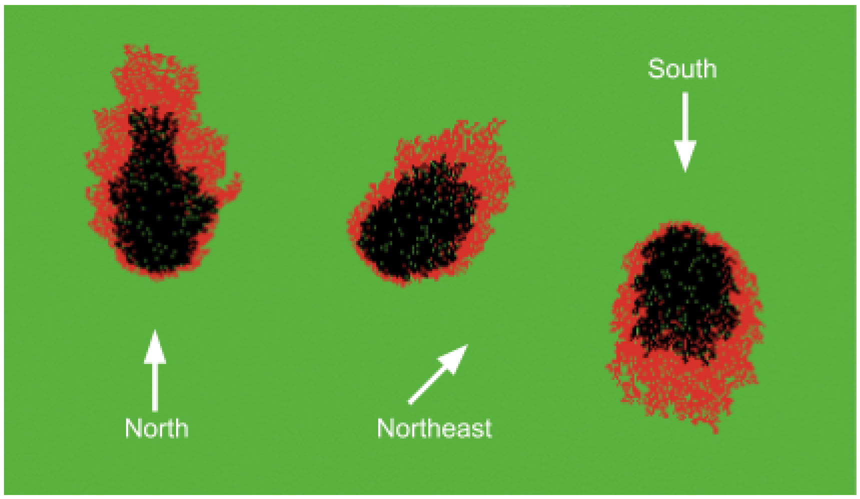


*Figure 13. Demonstration of the effects of wind on spread of fire. Arrows indicate wind direction.*

## 5. Results

### a. Phase Transitions in the Basic Computer Model

To identify the behavior of fire spread at different angles in the basic computer model (the computational replica of the physical model), we used the Netlogo "BehaviorSpace" tool to sweep through the incline angles (from -90° to 90° in increments of 5°) for all densities (from 10% to 100% in increments of 1%) with fire starting in the middle of the model. This data shows how the two variables (incline angle and density) interact to determine the average severity of a fire. We found that for every incline angle, the model will completely burn at 100% density, but will hardly burn at all (>0.1%) for densities less than 25%. Between these two extremes there is noticeable phase transition.

For each angle, there is a density that induces a phase transition: a sharp jump in the data where fires suddenly become much larger. Surprisingly, these phase transitions group together by angle into three definite sections. For angles between 0° and 20°, the phase transition is very sharp and occurs at around 40% density. For angles between 25° and 55°, the phase transition is slightly less sharp and occurs at around 50% density. For angles between 60° and 90°, the phase transition is not as drastic; the increase in percent burned rises gradually over a nearly 50% span of density increase before finally spiking at around 90% density (Figure 14).

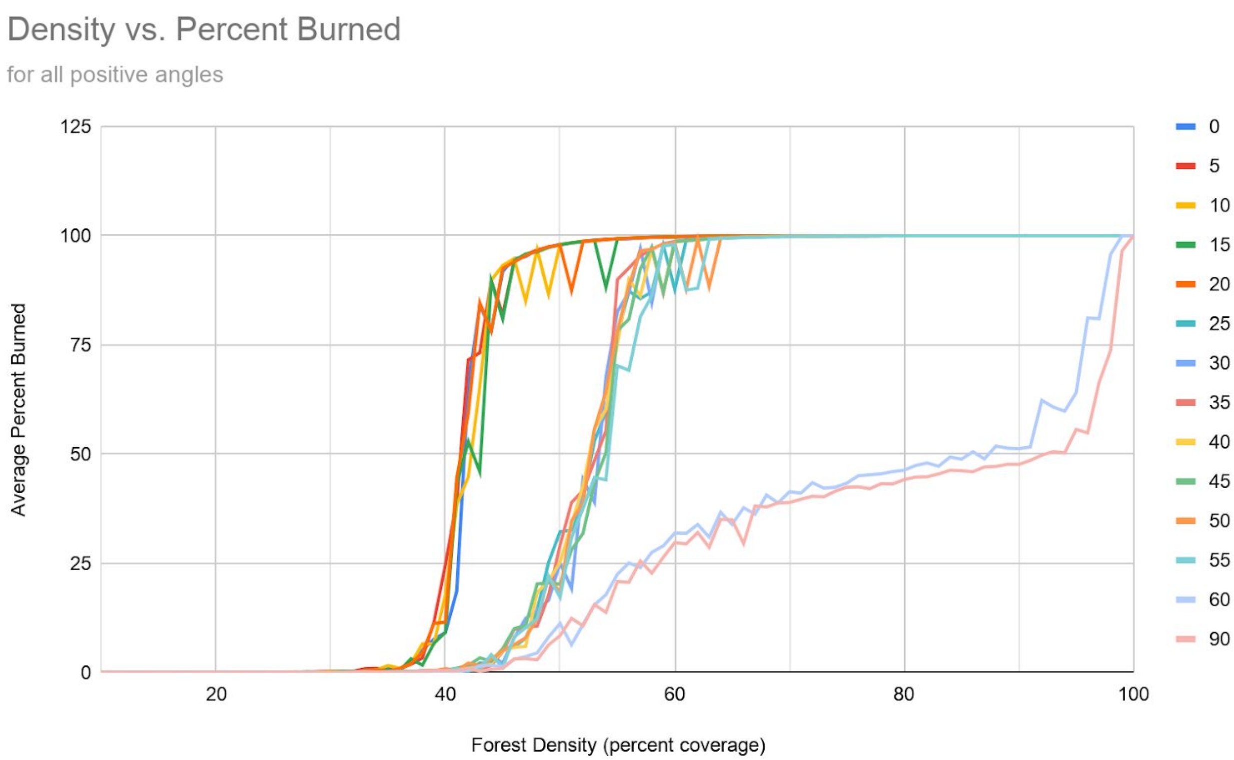


*Figure 14. Plot of the average percent burned at different forest density.*

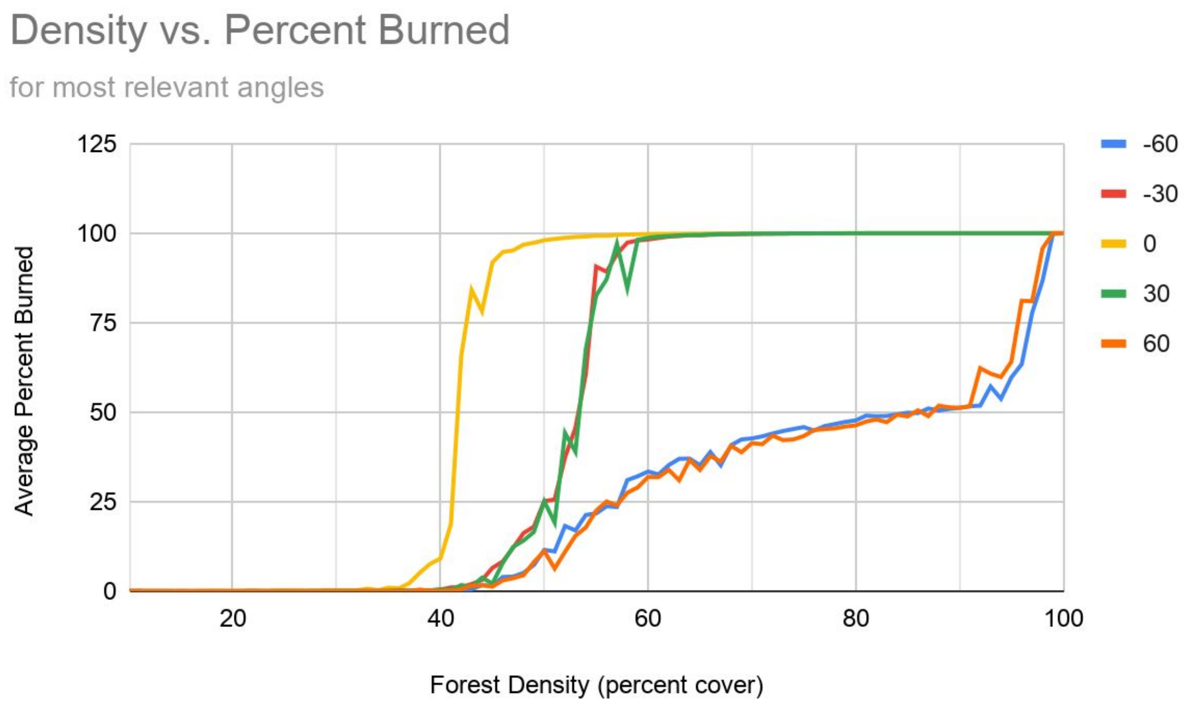


*Figure 15. Plot of the average percent burned at different forest density. Because the model started a fire in the center of the plane, the data is the same for both positive and negative incline angles.*

### b. Phase Transitions in the GIS Computer Model

We also wanted to investigate the effects of density on the severity of fire spread in Santa Fe using the GIS model. While the GIS groundcover and fuel-type data is useful for getting a current understanding of forest first risk in Santa Fe, it cannot be used to identify phase transitions. To identify the transition, we analyzed the model using <u>only</u> GIS elevation data (and randomly placed trees based on a set density). Similar to identifying the phase transitions in the basic computer model, this parameter sweep started a fire in the center of the plane and recorded the percent burned at forest densities from 10% to 100% (Figure 16).

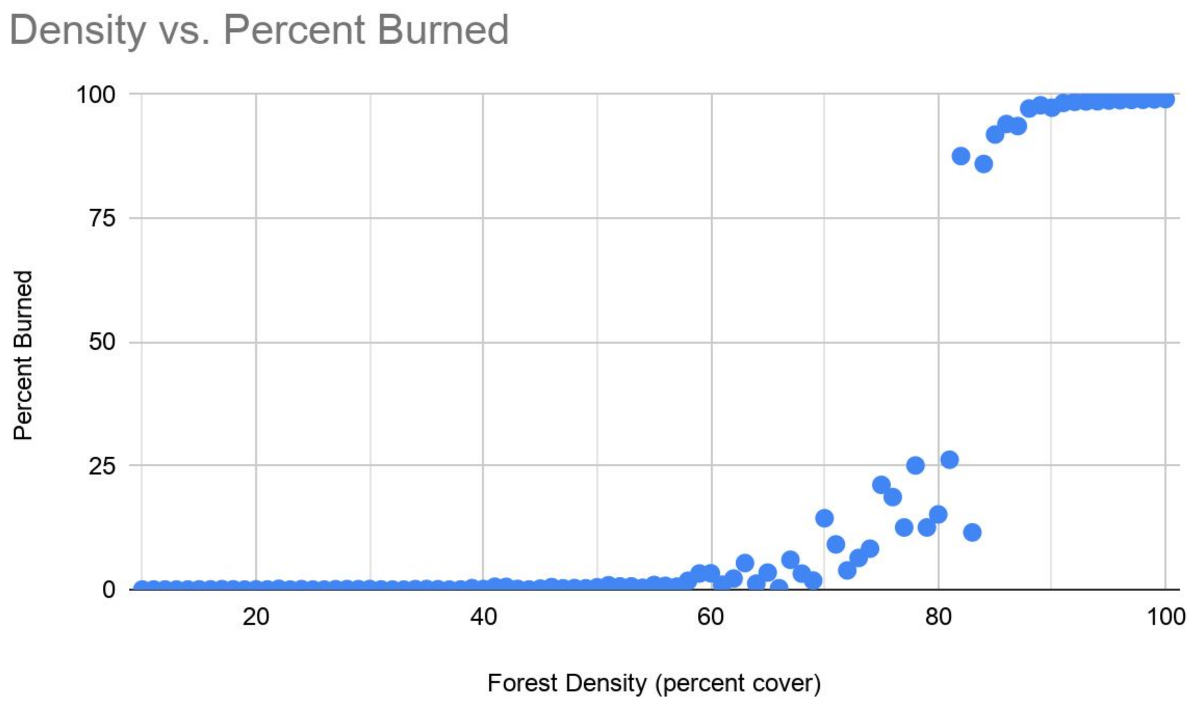


*Figure 16. Density and fire size indicating a phase change in the Santa Fe area.*

As expected, there is a clear phase transition in this data. The percent burned remains under 1% until around 58% density. The percent burned then grows with wide variation as the density increases. Then, at 84% density, there is a large jump in the data where the fire consistently burns around 100% of the forest for the remaining densities (Figures 16). In an animation depicting the size of a burn relative to the density of the forest, the phase transition can be visually observed. In the first frames of the animation with low density, only a small portion of the forest is burned while in the last frame with high density, nearly all of the forest is burned (Figure 17).

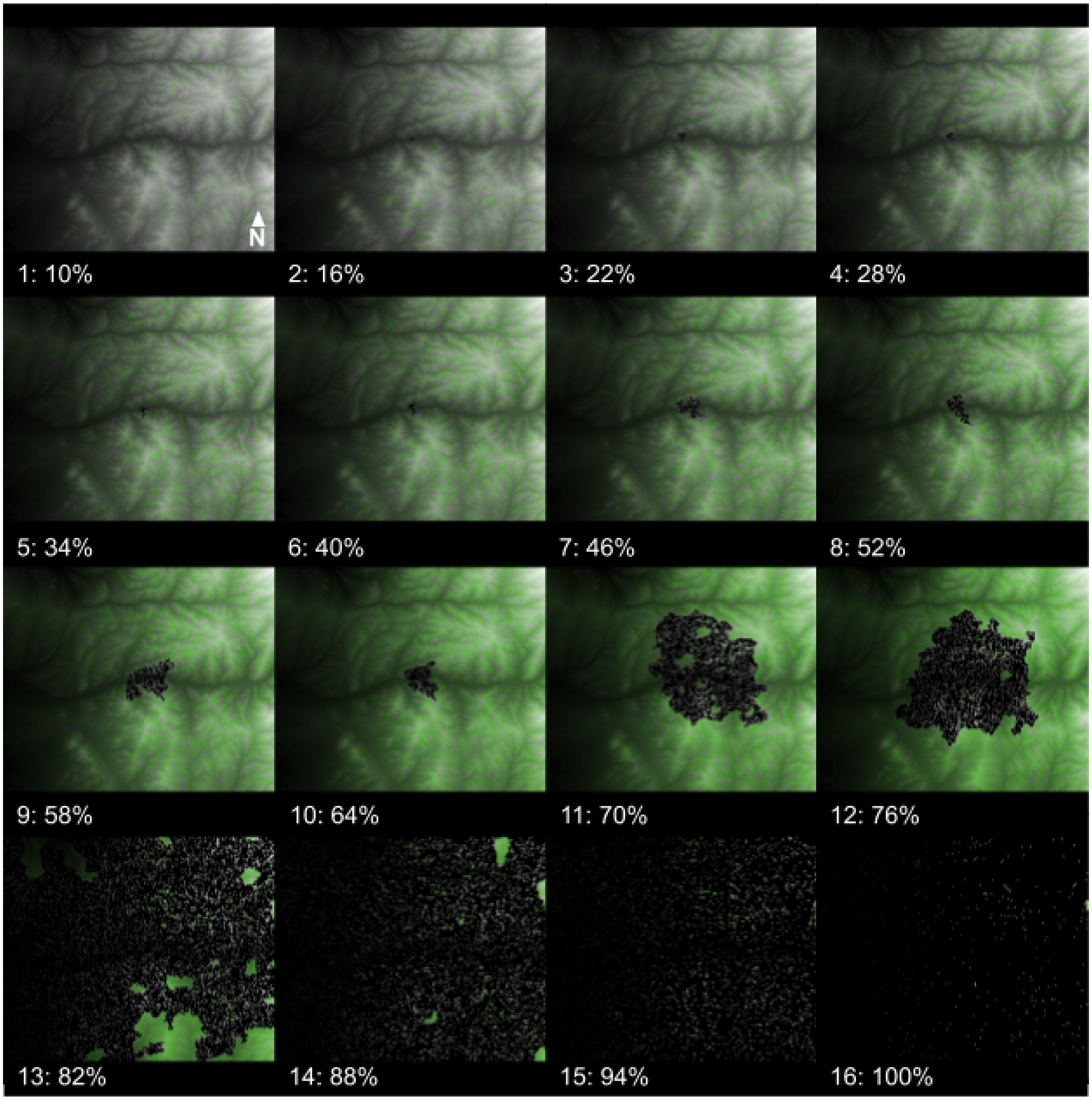


*Figure 17. Animation showing the phase transition in fire size as tree density increases in the Santa Fe area. The percentage indicates the forest density for each burn. The phase transition can be seen in frames 10 through 14 where the fires suddenly become much larger.*

### c. Mapping the "Fireshed" for Santa Fe

In the way that a watershed comprises all the sources of water and where they collect, the fireshed of a particular area comprises all of the locations at which a fire could start that would end up burning the particular area. Because each point has a distinct and unique fireshed, it is pointless to visualize them all. Instead, computing a fireshed should be used on a point specific basis such as identifying the risk a home has of being in the path of a fire. While it would be possible to expand the computer model with equations to efficiently and quickly compute the fireshed of a point, this was beyond the scope of the project. However, it is still possible to calculate the fireshed of a point without any further coding although the process is slow and inefficient. By conducting a burn at every ignitable location on the plane (not all patches can be ignition locations because not all patches have trees on them) and recording whether a target was burned, the fireshed for any location in our model could likely be computed in under 40,000 burns. Despite this, instead of computing a single specific fireshed, we decided that the most useful application of the model would be to generate a general fireshed inspired graph for the whole Santa Fe area (Figure 18). To do this, a fire was started at every ignitable location on the plane and the percent burned was recorded. With this data, we can predict the severity of a fire based on its origin. This is useful for identifying the areas of high risk in the area that deserve the most attention by the forestry service to ensure that a fire will not start there.

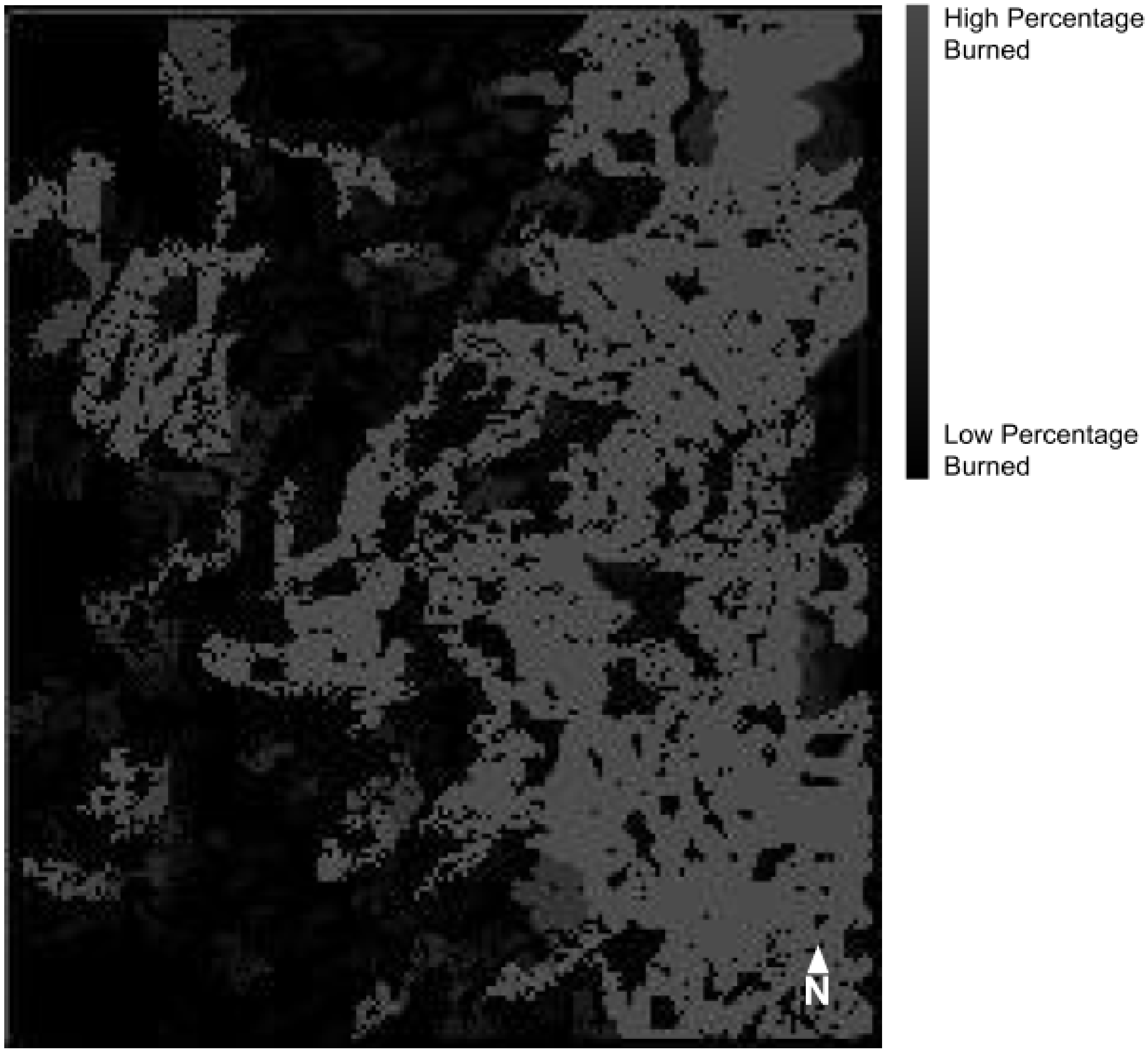


*Figure 18. Visualization of Santa Fe's fireshed in terms of high risk fire locations.*

## 6. Conclusion

### a. Takeaways

By the end of the project we were able to make a semi-realistic model of fire spread in the Santa Fe area that takes into account Sanat Fe's sloped terrain, unique groundcover, and variant winds. We started by designing and executing a physical experiment. The empirical data collected in the experiment was then used to develop a powerful equation that we could use in our computational model. The first and most basic computer model was designed to recreate the physical model allowing us to run experiments related to fire spread that exceeded the practical limits of a physical model. The second revision of the model introduced GIS elevation, groundcover, and fuel-type data into the code. This allowed the model to be applied to the exact terrain and ground cover of Santa Fe. The GIS data along with the slope-based fire spread equations tested in the basic computer model, allowed us to experiment with fire hazard in the Santa Fe area with the practicality and safety of a computer model. Finally, the variable of wind was added to make the model more comprehensive and representative of real world situations. With the completed model capable of showing the individual or combined effects of terrain, ground cover, and wind of the spread of a fire, parameter sweeps were used to identify meaningful phase transitions in the model. Then, as a final application, the model was used to compute the fireshed for Sanat Fe, highlighting locations in the area that are at high risk of triggering widespread fires.

### b. Limitations and Errors

Undoubtedly, the largest limmitination in this model originates in the application of the observations from the physical model to the real world in the computer model. It is obvious that forests do not burn the same way that a small sheet of paper burns yet in the model, we assume the two to be the same. Furthermore, as discussed earlier, the limitation of the computer model to allow fires to only burn in 8 directions will always affect the models accuracy. Avoiding this would require a complete restructure of the model to support a wider range of motion.

Additionally, in the GIS model, all fuel-type is burned the same way; a shrub burns at the same speed as a tree. By allowing the model to consider the different fuel-types with the ignition delay time calculation, it could be even more representative of the real world. Finally, the variable of wind was not based on empirical data. Instead we used our basic understanding of wind to develop a mathematical approach to include its effects on fire spread.

### c. Future Work

While the model that was created is certainly useful in learning about forest fires, as discussed previously, there are significant limitations in assuming a forest and a sheet of paper to burn the same way. The next step in perfecting the model would require further physical experiments to generate new data that more accurately reflect the rate of burn in a real forest. That being said, this project has paved the way to developing a greater understanding of the behavior of forest fires in the real world. While the model is still in its infancy, with more time, research, and experimenting, this model could easily become a powerful tool for firefighters, foresters, realtors, homeowners, and citizens alike.

## 7. Acknowledgements

We would like to express our gratitude for the support our teacher Mohit Dubey has provided us through the project. He has helped us troubleshoot our code, brainstorm our project, inspire our work, and teach us all valuable skills in the world of STEM. We would also like to thank our project mentor Stephen Guerin who has helped us integrate GIS data in our model as well as inspire us with his own interactive computer modeling sand table. Finally, we would like to thank everyone who is a part of the Supercomputing Challenge for nurturing our curiosity in STEM and providing us with an amazing opportunity to learn about computer science!

## 8. References

1. Andrews, Patricia L. *The Rothermel Surface Fire Spread Model and Associated Developments: A Comprehensive Explanation*. www.fs.fed.us/rm/pubs_series/rmrs/gtr/rmrs_gtr371.pdf.

2. Arthur, Damon. “Unprepared to Flee: Fleeing from Fires Is Common; Evacuation Planning Isn't.” *Fleeing Fires in California Is Common; Evacuation Planning Isn't*, Redding Record Searchlight, 13 Dec. 2019, www.redding.com/in-depth/news/2019/04/25/california-wildfire-evacuation-plans-not-required/3304823002/.

3. “Fuel Model.” *Wikipedia*, Wikimedia Foundation, 5 Aug. 2019, en.wikipedia.org/wiki/Fuel_model.

4. “Get Data.” *LANDFIRE Program: Get Data*, landfire.gov/getdata.php.

5. Las Conchas – Cerro Grande Fire Map 11:30 p.m. MT, June 29, 2011.

6. Rothermel, Richard C. “A Mathematical Model For Predicting Fire Spread in Wildland Fuels.” *USDA Forest Service*, Jan. 1972.

7. Whitewater-Baldy Complex Fire Map, June 2, 2012