Impact of Density on Wildfire Spread

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Section 1: Question

1.1 Modeling Question and Categorization

We pose the question: **What is the maximum tree density before an average of 25% of a forest will be actively burning during the peak of a wildfire?**

According to the specificity/action framework, our modeling question is primarily general and rhetorical. Our question is considered general since we deliberately do not specify the geography or ecology of our forest system. We aim for our model to be applicable to forest fires as a whole rather than specific forest types. Our question is rhetorical as the results of our model would be used to inform fire fighting and land management best practices.

1.2 Importance / Interest

According to the National Interagency Fire Center, over 56,000 wildfires burned in the United States in 2023. Collectively, these fires burned over 2.6 million acres of land. Wildfires cost the United States between 394 to 893 billion dollars per year, according to a report by the United States Joint Economic Committee. Beyond economic costs, wildfires kill, injure, and displace thousands of people every year. Given the significant human and economic costs of wildfires, it is important to understand wildfire behavior to mitigate these catastrophic outcomes.

The results of our model could be used to inform land management decisions. Controlled burns and forest clearings are proven methods to reduce the risk of catastrophic wildfires. Government agencies could use the results of our model to make informed proactive land management decisions to reduce the harms of wildfires.

1.3 Background Information

Our background research focused on the themes of forest density and wildfire spread. Through our research, we discovered that forest density varies dramatically, even within the same species [Source 3]. The Ponderosa Pine has an average density of 170 trees per acre [Source 1]. Wildfire spread increases with forest density, since high density areas contain more available fuel [Source 2]. More specifically, we found that fire spread followed a lognormal distribution, with a small number of extreme events playing a large role in the spread of forest fires [Source 4].

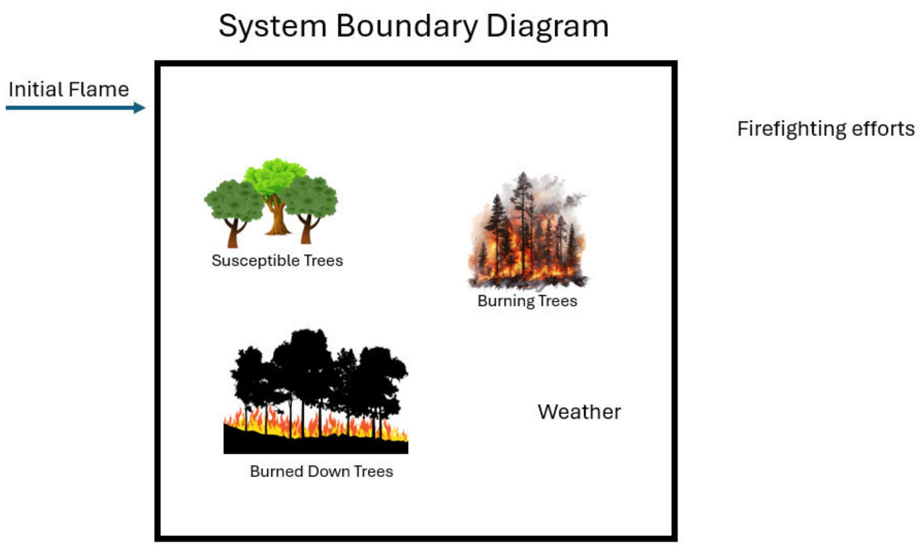
	Source 1: Modern Forest Management | California Policy Center	Source 2: Impacts of pre-fire conifer density and wildfire severity on ecosystem structure and function at the forest-tundra ecotone	Source 3: Stand Crown Fire White Paper	Source 4: Extreme fire spread events and area burned under recent and future climate in the western USA
Forest Density	Forest density is usually measured in trees per acre.	This research found that different landscapes had	Ponderosa Pine density can range from less than 100 Trees Per	Density is on of the factors that varies across a forest, leading

	In California's mid-elevation Ponderosa pine area, a wildfire-prone region, forests average 170 trees per acre.	varying levels of forest density.	Acre (TPA) to greater than 3000 TPA. Different sizes of trees also contribute to different densities. Quadratic Mean Diameter (QMD) is a metric to express the size of a tree.	to varying fire spread rates.
Fire Spreading	A crown fire is fire spreading through the canopy of a tree, and a ladder fire is a fire spreading through the trunks of the tree.	Fire severity increases with density due to an increase in available fuel. It could also be due to an increase in undergrowth, which is very flammable in certain conditions.	QMDs of +12" have a low probability of spreading for TPA less than 101, a medium probabbility of spreading for TPA of 102-262, and high rate of spreading for TPA greater than 263.	Fire spread follows a lognormal distribution, with a mean value of 295 hectares per day. Factors such as weather and forest composition impact the distribution. Extreme days account for a high percentage of fire spread.
Synthesis	Fire spreads through either the canopy or ladder of a tree, explaining why source 2 and 3 find that fire severity increases with density.	This source and source 3 both support that higher density forests increase fire severity.	This research provides distribuion data for probability of fires based on density. It is similar to source 4, however focuses primarily on the role of density.	This research aligns with Source 3 by describing a distribution for fire spread.

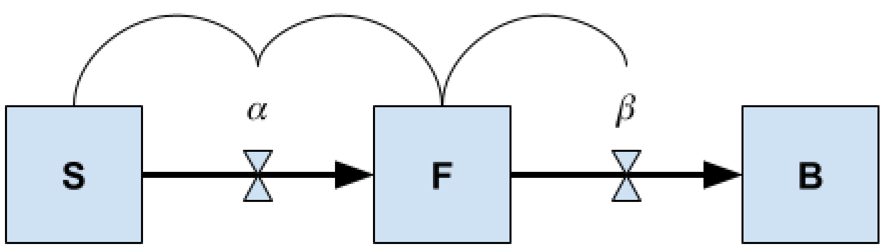
Section 2: Methodology/Model

2.1 Description

We define a system boundary and stock and flow model as the following:



Stock and flow model:



Symbol	Type	Meaning
S	Stock	Susceptible hectares of forest
F	Stock	Hectares of forest currently on fire
B	Stock	Burned hectares of forest
α	Flow	Rate of hectares that catch on fire
β	Flow	Rate of hectares that become fully burned

λ	Parameter	Fire strength (random; ex. dependent on wind, weather, etc), hectares burned per day
γ	Parameter	Density (deterministic), trees per acre

Flows:

$\alpha = \gamma * \lambda$

$\beta = 1 - \lambda$

Action Equations:

$$S_{i+1} = S_i - \alpha S_i$$

$$F_{i+1} = F_i + \alpha S_i - \beta F_i$$

$$B_{i+1} = B_i + \beta F_i$$

Assumptions

To feasibly create our model, we make a number of assumptions. Our research focused on trees from the Ponderosa Pine family, which are commonly found across California. In accordance with our research, we assume that our modeled forest contains trees with similar characteristics to Ponderosa pine. We assume a forest size of 100,000 hectares. Additionally, we assume that there are no firefighting efforts in our model. Finally, the cause of fire is not relevant to our modeling question, so we start every simulation with a single hectare of trees on fire.

2.2 Development

Parameters:

Fire strength (λ) is represented by the following log-normal distribution. The log-normal distribution features a pronounced right tail, representing how a significant portion of wildfire spread occurs on extreme days.

```
% Known values
m = 295; % Mean value ha/day, from research
standard_deviation = 200; % Standard deviation ha/day, from research
v = standard_deviation^2; % Variance

% Compute parameters - equations from lognormal distribution documentation
mu = log(m^2/sqrt(v+m^2));
sigma = sqrt(log(v/m^2+1));

% Create lognormal distribution
fire_strength_dist = makedist("Lognormal","mu", mu, "sigma", sigma);

% Visualize distribution
x = 1:10:1000;
bar(x, fire_strength_dist.pdf(x));
```

```
title("Lognormal distribution", "Mean = 195, Standard deviation = 200");
xlabel("Fire strength (\lambda): Hectares burned per day");
ylabel("Probability");
```

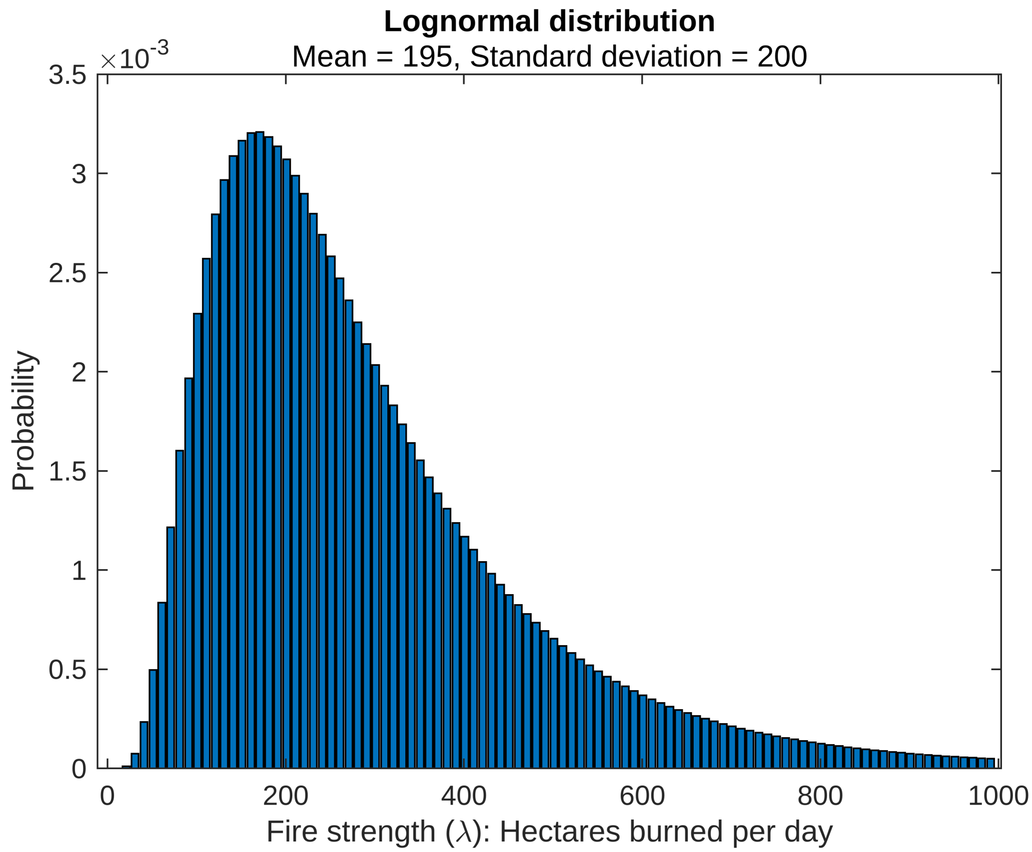


Figure 1: Lognormal distribution used to generate fire strength (λ) parameter.

Density (γ) is a modifier from 50% to 150% (0.5-1.5).

```
num_densities = 20; % Number of different densities to test
gamma_vals = linspace(0.5,1.5,num_densities); % Generate modifiers from 50%
to 150%
```

Simulation

```
% Starting values (in hectares)
s_0 = 100000 - 1;
f_0 = 1;
b_0 = 0;
total_hectares = sum([s_0 f_0 b_0]);

num_steps = 50; % Timesteps
num_simulations = 1000; % Number simulations for each density

% Allocate space for results
S_results = zeros(num_steps, num_simulations, num_densities);
F_results = zeros(num_steps, num_simulations, num_densities);
```

```
B_results = zeros(num_steps, num_simulations, num_densities);

% Iterate through each gamma value
for i = 1:length(gamma_vals)
    gamma = gamma_vals(i);

    % Run simulations
    for j = 1:num_simulations
        [S, F, B, W] = simulate_sfb(s_0, f_0, b_0, fire_strength_dist,
gamma, num_steps);
        S_results(:, j, i) = S;
        F_results(:, j, i) = F;
        B_results(:, j, i) = B;
    end
end

% Visualize results
figure()
for i = 1:length(gamma_vals)
    plot(W', mean(F_results(:,:,i),2), "DisplayName", "Density:
"+gamma_vals(i)); hold on;
end
yline(total_hectares*0.25,"r--", "DisplayName", "25% of Forest")
ylabel("Average number of hectares currently on fire");
xlabel("Timestep (Day)");
title("Hectares on fire over time (Full Graph)");
axis([0 num_steps 0 total_hectares]);
legend();
hold off;
```

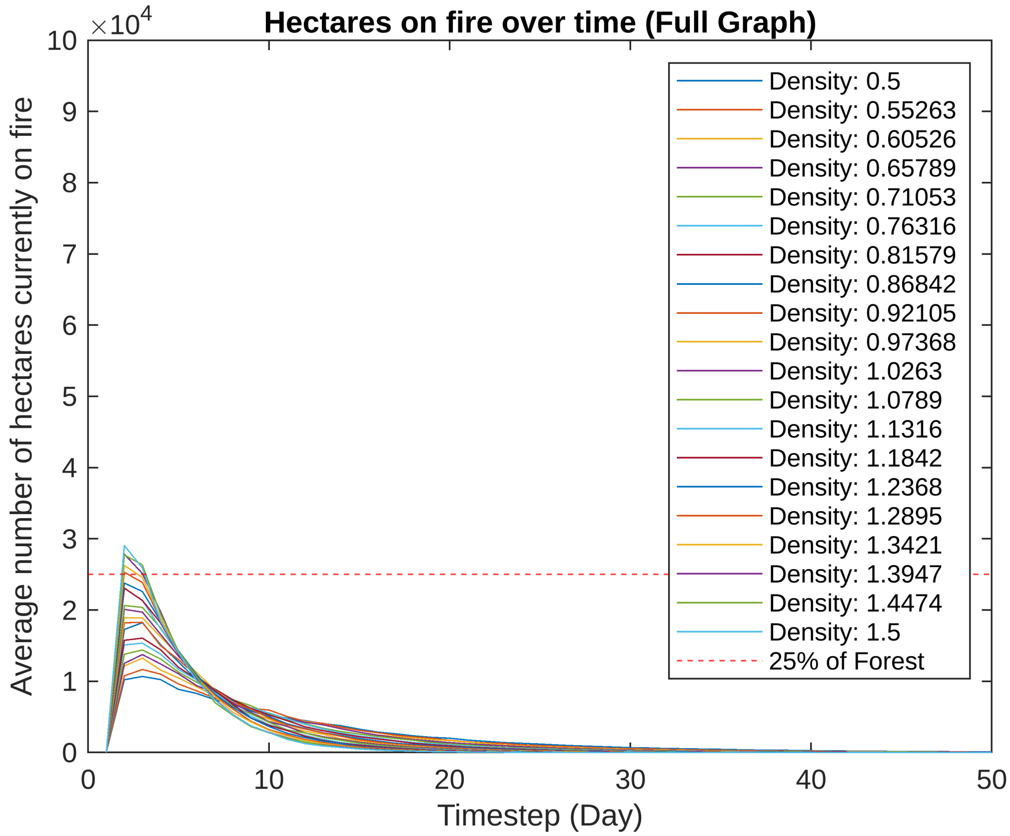


Figure 2: Graph comparing the average number of hectares currently on fire for each density at each time step.

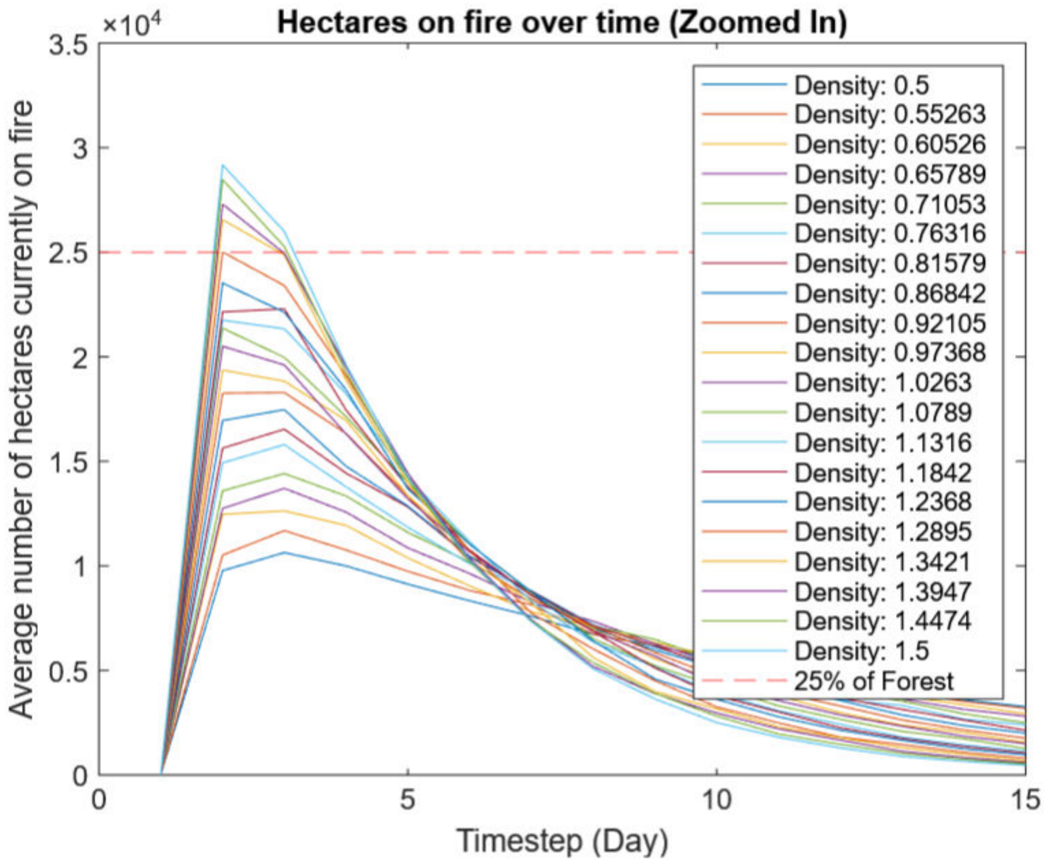


Figure 3: Zoomed in section of Figure 2 to show where average values meet the 25% of the forest threshold.

Verification

We employ assertions to verify our model's performs as we designed.

```
assert(max(max(max(F_results))) <= total_hectares , "The number of trees
burning at once cannot exceed the total trees.")
assert(max(S_results + F_results + B_results, [], "all") <= total_hectares,
"The sum of trees in all states cannot exceed the total number of trees.")
disp("Assertions Passed!")
```

```
Assertions Passed!
```

2.3 Validation

We validate our model by comparing general characteristics with historical trends of forest fires. The average forest fire duration is 37 days (FaceTheFactUSA). On day 37 of our model, less than 0.5% (500 hectares) of the original forest is still burning across all densities, as seen in the below graph. We consider the fire to be concluded once this threshhold is passed.

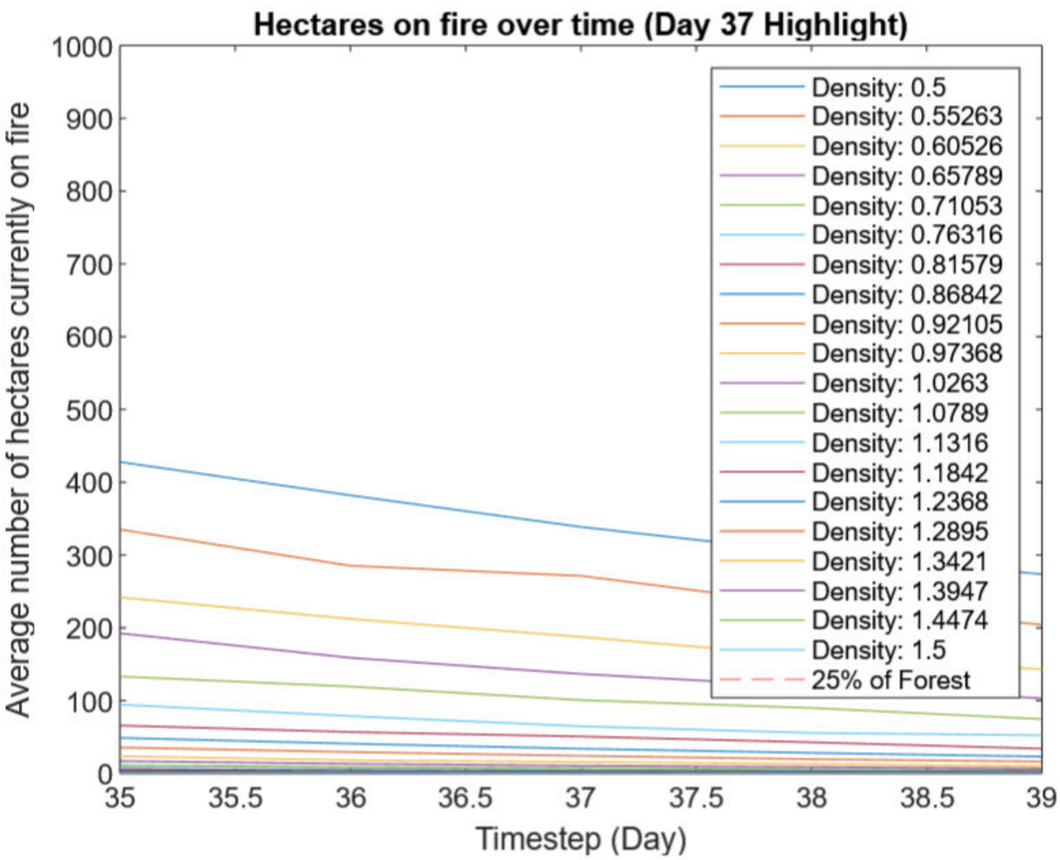


Figure 4: Zoomed in section of Figure 2 highlighting the the graph's behavior at day 37. The average number of hectares currently on fire for every density is below 500.

2.4 Deterministic or Random Quantities

We represent fire strength as a random parameter to model randomness in weather conditions between days of a wildfire. Each day, a new sample is chosen from the distribution. Density is represented as a deterministic parameter because our modeling question seeks to determine the density where an average of 25% of a forest will be actively burning during the peak of a wildfire.

Section 3: Results

3.1 Metrics and Sweeps

The metric we identified is **average peak number of hectares burning**. We perform a sweep over the density values to determine where the average peak number of hectares burning is greater than 25% of the forest.

```
% Find peak number of average trees burning for each density
peak_burning = reshape(max(mean(F_results,2)),[],20);

% Visualize
figure()
plot(gamma_vals, peak_burning(1:20), ".-", "MarkerSize",5, "DisplayName",
"Peak number of hectares burning");
yline(total_hectares*0.25,"r--", "DisplayName", "25% of Forest");
```

```
xline(1.3, "m--", "DisplayName", "Density Multiplier = 1.3")
ylabel("Average peak number of hectares burning");
xlabel("Density Multiplier (%)");
title("Density vs. average peak number of hectares burning");
legend()
```

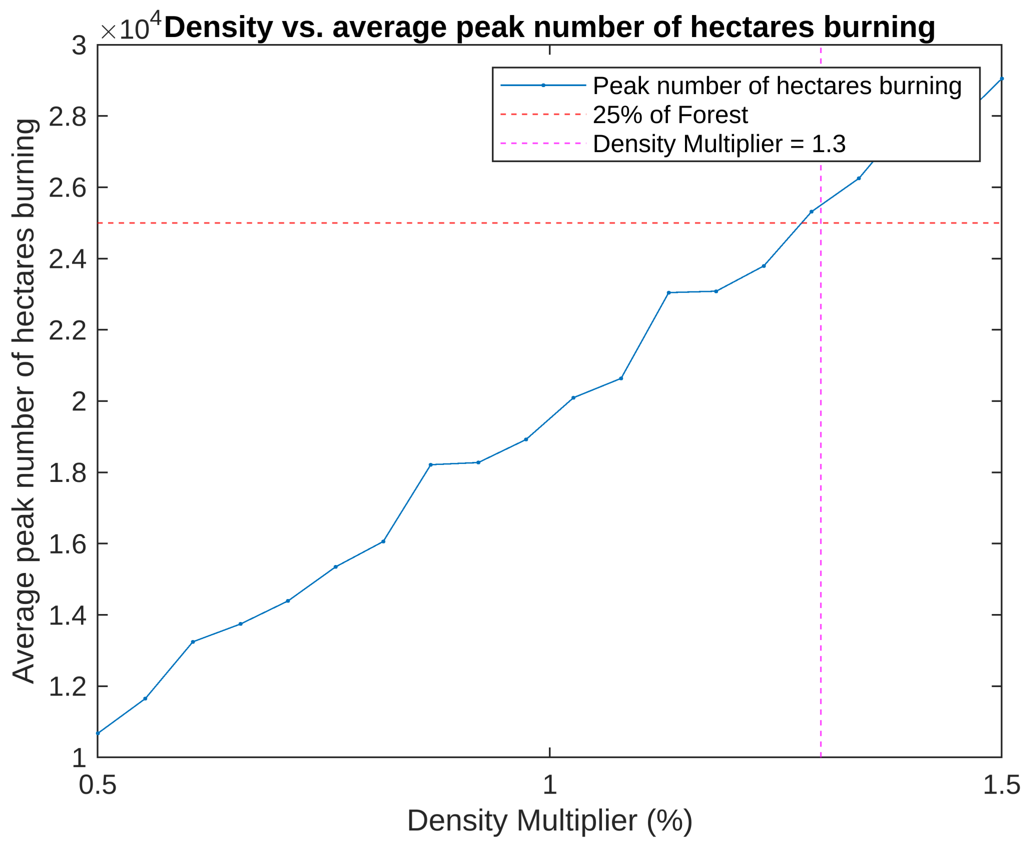


Figure 5: Parameter sweep between density multiplier value and average peak number of hectares burning. Dashed red line represents the 25% of the forest threshold.

3.2 Analysis

From the above parameter sweep, we can see that the density multiplier that results in the average peak number of hectares burning to be greater than 25% is approximately **1.3**. In other words, 130% of the baseline density is the answer to our modeling question.

From our research, we discovered that the average trees per acre of our forest was 170 acres. Converting acres to hectares, we are left with an average trees per hectare value of approximately 69. Multiplying 69 by our density multiplier of 1.3, we get 90 trees per hectares.

This means that when forest density reaches 90 trees per hectare (~222 trees per acre), an average of over 25% of the forest will burn at the peak of a wildfire.

Section 4: Interpretation

4.1 Therefore

To ensure that no more than 25% of the forest burns at a given time, firefighters should implment forest management practices to reduce tree density to fewer than 90 trees per hectare.

4.2 Limitations and Future Work

Our model has several limitations due to the assumptions we make. First, we assume that the forest in our model consists of trees with characteristics similar to Ponderosa pine. For forests with diverse tree ecology, this may be inaccurate. Second, the forest size is fixed at 100,000 hectares. Additionally, we do not account for any firefighting efforts, which could influence fire spread. Lastly, we assume that the cause of the fire is irrelevant to our analysis, and each simulation begins with a single hectare of trees already burning. In the future, we could model a more complex forest, capturing the differences that exist within the geography and ecology of a forest.