Agent Based Modelling: Forest Fires Spreading and Extinguishing

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Abstract

The forest fire in Australia is heartbreaking. In order to find the best strategy to put out the fire, forest fire model has been created by agent-based modeling. Beta distribution has been used to generate the initial density of forest which was obtain the real data from Queensland. Two strategies-extinguish and fireline has been tested. For the local sensitivity analysis fire spread parameter was the most important parameter for both two strategies. Local sensitivity analysis showed that 0.005 is threshold point where fire would become unmanageable and epidemic. Furthermore, extinguish strategy was the better strategy when all the parameters are fixed.

Contents

1 Introduction

Given recent events, the forest fires in Australia lasting for several months is heartbreaking. Experienced with such a disaster, human beings should reflect on many aspects, one of it is that how to put out fire timely. In this paper, the forest fire case is studied based on an Agent-based model. The aim is to explore different abstractions of reducing spread of forest fires and thus minimizing the harmful effects. Previous research [6][5] shows that regular endemic and controlled forest fires aid in preventing epidemic fires.

The combination of weather conditions and diversity of biomass in Australia forms an extremely fire prone country, recently we have seen detrimental effects all over the country shutting down airports and invading urban areas [2]. Thus we shall present a model that explores how different fire fighting strategies can mitigate the destruction of forest fires. First we should be able to alter parameters of the fires spread to match that of real events and then implement different strategies, exploring which strategy is more effective.

2 Model Description

2.1 Purpose

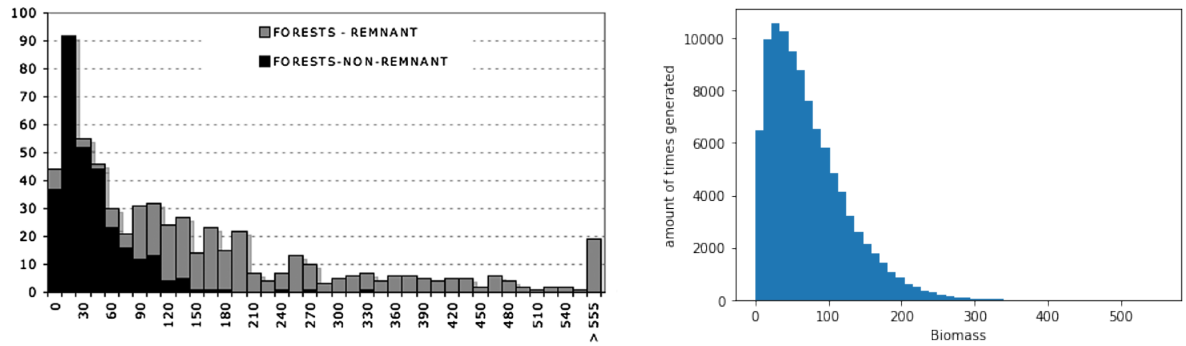
The first objective of this project is to explore the spreading dynamics of forest fires, in particular in Australia. Using data to fit the spread of the fire through our simulated space, to a real (epidemic) forest fire should be possible. We should be able to easily expand and change our model to incorporate new factors, or to better fit collected data.

Then, We will incorporate the idea of firefighters that will attempt different strategies to put out the fires, and give an insight into which strategy minimizes the epidemic effect of the fire.

2.2 Entities, State variables and Scales

Environment: The environment of our model is a grid space where the agents live. We have two types of agents, fire fighters and forest, which we will discuss in further detail later. In our model the environment is static since the environment has no dynamics at the moment. It is also fully accessible since on the time scales our model operates and modern communication technology we can assume our fire fighter agents have complete up to date information. However in 2018 there was a case where Verizon throttled the data plan of California's fire department during the wildfires [1], which had significant impact on the fire fighters ability to do their job.

The environment determines how much forest or how many firefighters are present in the environment. The number of fire fighters is a constant, but the amount of forest that is initially present is probabilistic. We created a probability distribution that mimics the forests in Queensland Australia [4], this distribution seems to be be a beta distribution, in figure 1 we show the comparison between the observed data and our probability distribution.



(a) reference data from forest density observations in Queensland [4], biomass measured in Mg/ha

(b) Random data generated by a beta distribution, alpha=1.5, beta=10, scaled to the range 0-555

Figure 1. Forest density distribution

Agents: **(1)** The first agent we introduced in the environment was a section of forestry that spans an area of about 1 hectare (1 ha = 10000 square meters). The section of forest has a certain density, which is measured in biomass per ha. And the section of forest can have two states, on fire or not on fire. If a section is on fire it has the ability to spread the fire to its Moore's neighbourhood, this is linearly dependent on the neighbours density. Consequentially the likely-hood of a tree catching fire is proportional to the number of burning trees in its Moore's neighborhood.

(2) Our second agents are the fire fighters, the fire fighters have the ability to apply different strategies to reduce the effect of the forest fire. **(a)** Our first strategy is extinguishing fires, the fire fighters extinguish fires by attacking the fire in a section of the forest directly, the fire that is chosen is random. This extinguish action has a chance to succeed or fail which is negatively correlated to the density of that section of forest which the fire fighter is trying to extinguish. There is only a single parameter in our model that influences this strategy and that is the difficulty of putting out a fire in general. **(b)** The second strategy is using firelines (sometimes called a firebreak). When there is a fire the firefighters will create a boundary around the fire where they remove all flammable material as quickly as possible to prevent the fire from spreading further than the boundary. For this strategy we have two parameters, the distance between the fire and the fireline, and the amount of forest a firefighter can remove in a single step.

2.3 Process overview and scheduling

Initially the environment is generated, in every grid space the density of forest is randomly drawn from a beta distribution, the parameters are defined in the environment as paper [4], and as seen in figure 1. The forest section agents have *density, position* and *fire state*. After setting a the *fire state* to *true* of a tree at a random position at initialization, the fire can spread to neighboring cells to simulate the forest fire. The chance of the fire spreading to a neighboring cell is linearly dependent on the density of neighboring cells.

In the model, there assumes a period of delay before firefighters starting to put out fire, in order to observe a severe fire. Since in practice, severe fire is more destructive and worthy of study, exactly like the Australia

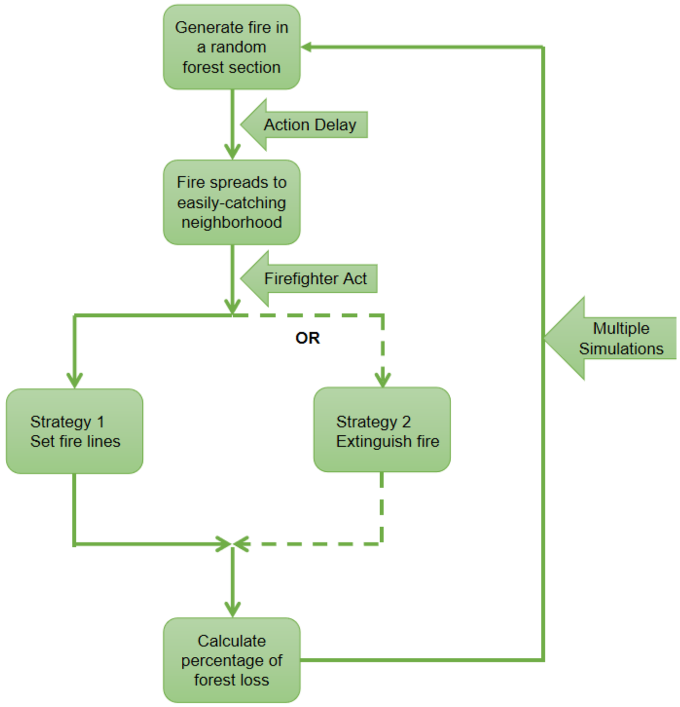


Figure 2. An overview of model dynamic steps.

fire in this model.

After the delay period, the firefighters take action to put out fire. And two strategies are studied one by one to find which strategy performs better in decreasing forest loss. For each strategy, multiple simulations are carried out since every time the fire spread and put out process are stochastic.

Table 1. Parameter descriptions,bounds

Category	Attributes	Parameter description	Bound
Environment	width/height	number of grids in each column and row	[20,100]
	fire spread param	the speed of the fire spreads	[0.003,0.006]
	number firefighters	the number of the firefighters in the environment	[0,20]
	initial distribution alpha	density of the forest-α	1.5
	initial distribution beta	density of the forest-β	10
Tree Agent	density	biomass in each grid	[0,555]
	on fire	the state of the tree	
Firefighter Agent	strategy	strategies of the firefighter to put out the fire	
	response delay	delayed days after the fire outbreaks of firefighters	[1,5]
	extinguish difficulty	difficulty for firefighter to operate extinguish strategy	[1,5]
	fire line margin	distance from fire to start firelines	[1,5]
	cut down amount	Amount of density able to remove for fireline	[100, 555]

2.4 Design Concepts

2.4.1 Basic principles

- The distribution of biomass in each forest section (grid) obeys beta distribution, beta (α,β). And the maximum biomass of each section is 555 (trees) in Queensland, see figure 1.
- When the centering cell is catching fire, the possibility of catching fire for any neighboring cell i, $P_c(i)$ =neighbors[i].density $\times$ fire spread parameter.
- The firefighters start to take action after a delay of several time steps.
- The firefighters have two choices of put out fire strategy. In this model, multiple simulations will be done for each strategy to get an average percentage of forest loss, due to stochastic property of model.
- The percentage of forest loss includes the forest loss caused by cut down trees when firefighters are taking actions to put out fire.

2.4.2 Emergence

With the use of different spread parameters we see the characteristics of the fire spread quicker and destroy more forest at a faster rate. When there is a large area of dense forest we notice the fire spreads quicker through that section. When we execute the different firefighting strategies we notice that the fire-line strategy does not depend on the density of forestry as much as the extinguish strategy, where the denser the forest is the harder it seems to be for the extinguish strategy to fully extinguish the fire.

2.4.3 Objectives

- In the extinguish fire strategy, the objective of the firefighter is to extinguish the fire after a certain time. This can not always be done successfully, so there is a parameter in our model *extinguish difficulty* which determines the probability of successfully putting out a fire. Putting out fires also becomes more difficult for denser sections.
- In the fireline strategy, firefighters start to establish a fire control line to stop fire spreading after a certain delay time. However, they need to keep a distance from fire for their safety. This distance is defined as a variable *margin* in this model.

2.4.4 Interaction

The only communication between our agents is the communication to the Moore's neighbour hood during the spreading of active fire. A burning forest agent communicates directly with its eight neighbours and try to actively set them on fire.

2.4.5 Stochasticity

In every grid space the density of forest is drawn from a beta distribution, which corresponding to the data biomass of queen's land [4], and seen in figure 1. And the position of where the fire starts and the position of firefighters are random. Under each strategy study, the fire severity in each simulation is different and it will make firefighters take different amount of steps to put out fire.

2.4.6 Observation

When we simulate from the model the most interesting observations are the percentage of forest loss and burning time. The percentage of forest loss tells us the estimated damage to the surrounding area and the burning time can tell us how long it took for a certain strategy to control an outbreak.

2.5 Initialisation

parameter	set fire lines	extinguish fire
environment scale	50×50 grid	50×50 grid
number firefighters	10 people	10 people
firefighter response delay	2 days	2 days
extinguish difficulty	-	10
cut down amount	200 trees per step	-
fire line margin	5 grids	-
α, γ of beta distribution	1.5, 10	1.5, 10

Table 2. Initialization of model for different strategies. For each strategy keep the environment strategy the same. The other special parameters is in line with most practice situation.

2.6 Sub-models

Firefighters can operate different strategies. Extinguish and fireline strategy's algorithms were showed as follow. And the process showed as Figure 3.

Algorithm 1 Extinguish strategy

Result: Percentage of loss, Burning time

initialization

if *Timestep>=delayed time* **then**

  while *any Tree.onfire* **do**

    move to a tree that is on fire

    if *Firefighter succeed* **then**

      extinguish fire

    end

  end

end

Algorithm 2 Fireline strategy

Result: Percentage of loss, Burning time

initialization

if *Timestep>=delayed time* **then**

  bbox = find bounding box around fire

  fireline = add *margin* to boundaries of *bbox*

  while *any Tree.onfire* **do**

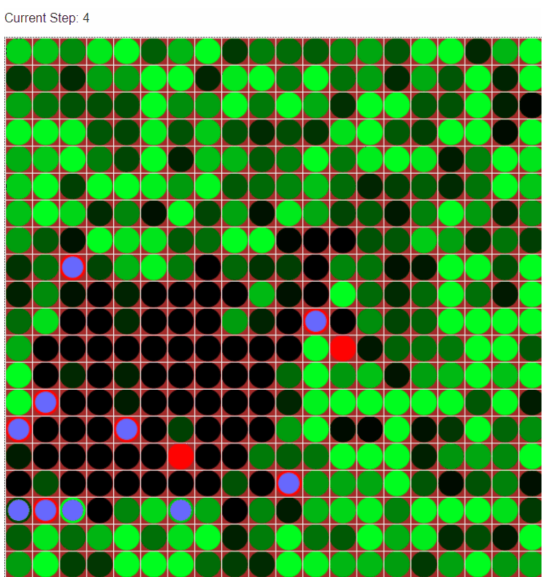
    tree = find tree with highest density on *fireline*

    move to *tree*

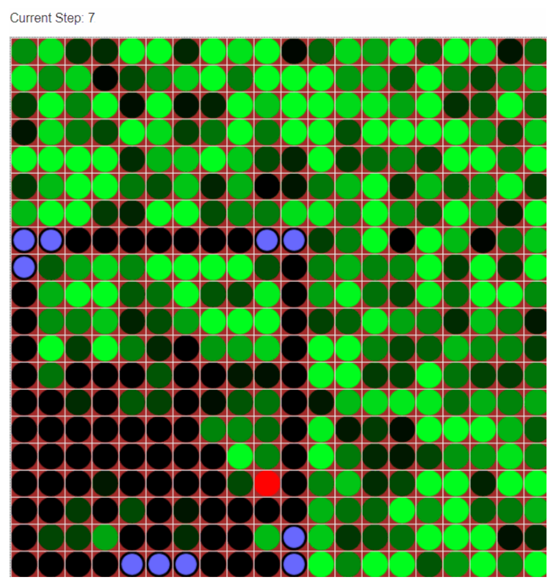
    cut down *tree* by *cut down amount*

  end

end



(a) Extinguish strategy, black grid-after burned, red grid-on fire, blue grid-firefighter



(b) Fireline, black grid-after burned, red grid-on fire, blue grid-firefighter, square - fireline

Figure 3. Two strategies

2.7 Output

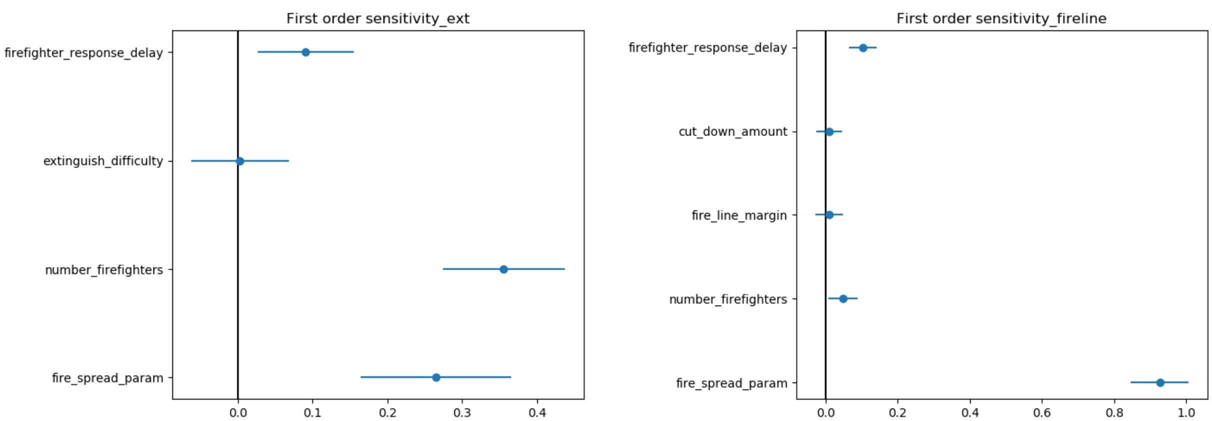
The model's output are percentage of loss and burning time. Percentage of loss is the percentage of how many grids have been burned down in each step. And the burning time is how many steps the fire lasted.

3 Sensitivity Analysis

3.1 Global Sensitivity Analysis

Global sensitivity analysis is the method to determine the most important parameters for the whole input range. In this part, all the parameters' bound were listed in Table 1. And the output are percentage of loss and burned time.

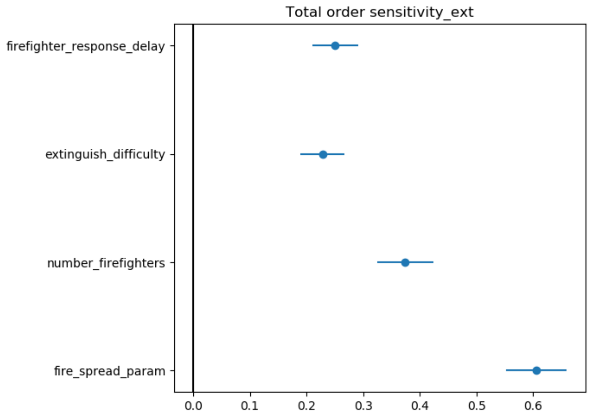
For the first order sensitivity(Figure 4), it is clear to see that the in the extinguish strategy number of fighter and fire spread parameter had greater value than extinguish difficulty and response delay. While in the fireline strategy, only fire spread parameter had great impact.Total order sensitivity for two strategies are introduced in this part, first and second order sensitivity are listed in appendix. As Figure5(a) shows, fire spread parameter is the most sensitivity parameter in extinguish strategy. Because the firefighters cannot stop the fire in a short time when fire spread too fast and become an epidemic fire. Figure5(b) also shows the fire spread parameter compared to other four parameters in fireline strategy, which because when fire can easily cross the unfinished fireline when fire spread parameter increases.



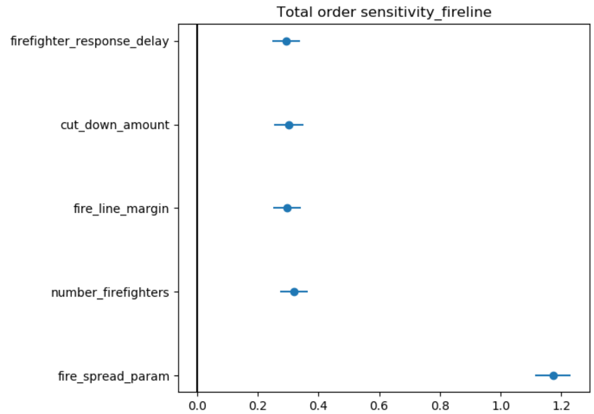
(a) First order sensitivity of extinguish strategy

(b) First order sensitivity of fireline strategy

Figure 4. Global sensitivity analysis-first order



(a) Total order sensitivity of extinguish strategy



(b) Total order sensitivity of fireline strategy

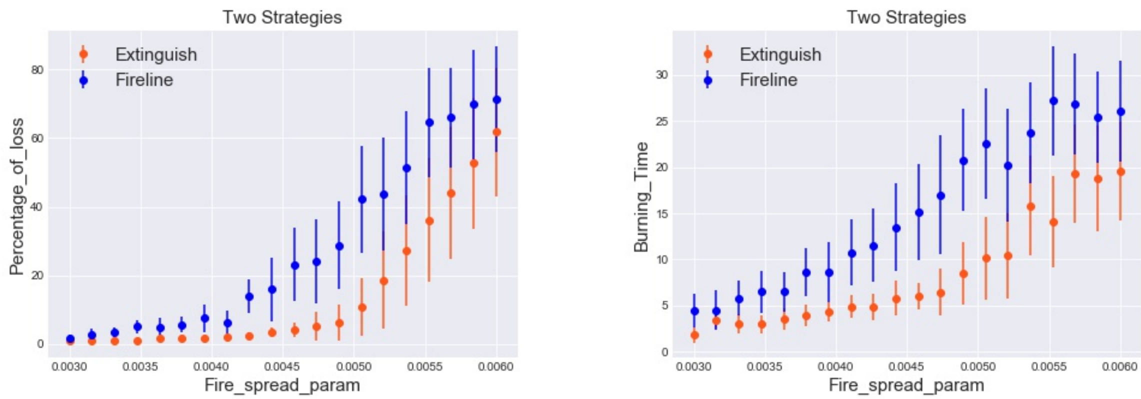
Figure 5. Global sensitivity analysis-Total order

3.2 Local Sensitivity Analysis

Local sensitivity is the method to determine the local impact of variation in input. Based on the global sensitivity analysis, fire spreading is the most sensitive parameter and the fixed parameters shows as Table 3. Thus, the results of fire spread parameter in OFAT showed as Figure 6. As Figure 6(a) shows, as the fire spread parameter increase two strategies show similar trend for the percentage of loss. The percentage of loss of fireline strategy was always greater than the extinguish stategy, which because fireline strategy has margin distance to the fire. For the extinguish strategy when fire spread parameter is smaller than 0.0050 the percentage of loss increased slowly. Then, the percentage of loss increased quickly when spread parameter is bigger than 0.0050, which means 0.005 is threshold point which the fire become epidemic for the given parameters. Figure 6(b) shows the burned time respects to the fire spread parameters, it has the same trend as the percentage of loss and extinguish strategy always show better performance than fireline strategy.

Table 3. fixed parameters for local sensitivity to fire spread parameter

Parameters	**Bound**
width/height	50
fire spread param	[0.003,0.006]
number firefighters	10
response delay firefighters	2
extinguish difficulty	2
fire line margin	5
cut down amount	200

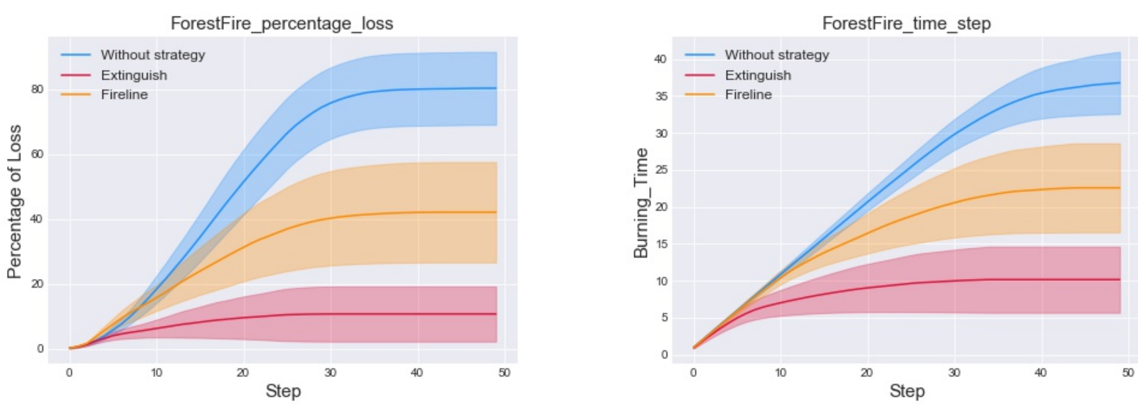


(a) Percentage of loss respects to the fire spread parameter (b) Burning time respects to the fire spread parameter

Figure 6. Local sensitivity of Two strategies

4 Simulation and Discussion

After local sensitivity analysis, in order to determine which strategy has better performance, fire spread parameter was fixed as 0.005. Other parameters were showed as Table 3. As Figure 7(a) and Figure 7(b) shows, both extinguish and fireline strategies were effective to decrease the percentage of loss and burning time. Extinguish strategy show better performance than fireline in the given parameters. One reason is that the fireline strategy has margin distance which would increase the burned area and time. Another reason is in the current model the extinguish strategy didn't consider the water source, road and so on factors, which makes the extinguish is too "effective". But currently the extinguish strategy has better performance to put out the fire.



(a) Percentage of Loss comparison, simulation times=100 (b) Burned time comparison, simulation times=100

Figure 7. Comparison of two strategies

5 Conclusion and Future Work

In this project, forest fire model has been created to determine the best strategy to put out the fire. It is clear to see that agent-based modelling is a effective method to simulate the forest fire. For the sensitivity analysis, the global sensitivity analysis showed that for both strategies fire spread parameter is the most sensitive because it determined whether the fire is manageable for firefighters. After global sensitivity analysis, local sensitivity analysis has been done for fire spread parameter. When fire spread parameter is bigger than 0.005, the percentage of loss and burning time increased significantly and become a epidemic fire. The better effective strategy has been determined by fixed parameters. Though two strategies both could decrease the percentage of loss and burning time, the extinguish strategy are better. Because fireline strategy had margin distance.

Future work could either extend the environment or create more strategies. For the environment part, wind speed and direction are important to simulate forest fire. Because wind has influence on fire direction and size, changing the probability of neighbors catching on fire. Forest also could have growth rate which has different rate in different season. Besides, in order to validate the model, model can be designed to simulate the actual terrain such as park, forest and so on. Then the data can be easily collected. For the strategy part, extinguish strategy should also consider the water source and real road. Furthermore, wetting trees, using bombs [3], and so on can be added into the model to determine which is the most effective strategy.

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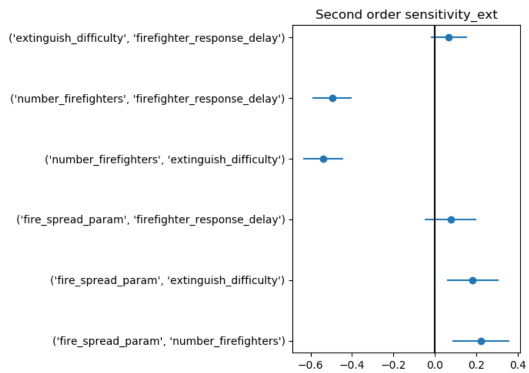
7 Appendix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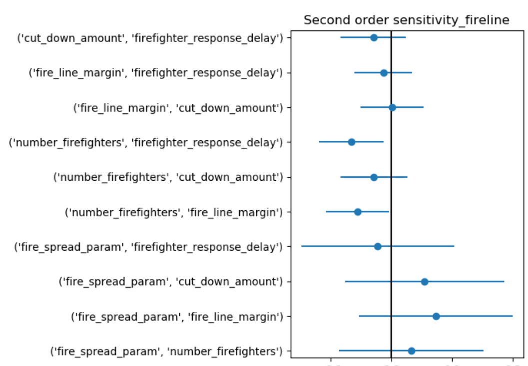
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