Utilization of Cellular Automata to Simulate Forest Fire Spread

Complex Adaptive Systems Final Project

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- Original concept creation and literature search
- Additional cellular automata concept expansion
- Figure creation
- Final paper

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- Additional cellular automata concept expansion
- Python code creation
- Simulations

Abstract

Forest fire success is a combination of ignition location, the ability of vegetation to ignite, usually a result of moisture content, and the amount of fuel present in the area. Our model addresses the trade-off between ignition ability and vegetation fuel value, common in actual forest regimes. Fire success and behavior in a region of interest which displays complex behavior indicate that fuel value may be ultimately more important than ignition ease in the overall fire success. Furthermore, increasing wind speed may decrease fire success if it funnels the fire towards a natural or manmade barrier that cannot be easily jumped.

Introduction

Forest fires are a common occurrence in the United States, on average from 2005-2014 there were 18,995 fires, burning a total 713,063 acres each year. These fires can be necessary for ecosystem function but also often pose a threat to inhabited areas. As a result numerous governmental agencies are interested in predicting the spread of forest fires for proper containment and forest management. There are a multitude of strategies employed to predict forest fire movement, including differential equation based models, wavelet propagation algorithms, and cellular automata simulations. These models often use topography and fuel data derived from GIS maps. We propose a general cellular automata framework for forest fire simulation which employs variation in vegetation and wind movement. This structure is robust in that it can be generally applied to various vegetation regimes.

We explored the relative impacts of a simple vegetation mosaic and wind on the fire behavior and overall fire success, measured as the percentage of the cellular automata completely burned at convergence. Specifically, the median final percentage of the cellular automata burned over numerous simulations was found for all combinations of wind speed and vegetation combinations. The sensitivity of fire success to some of our model parameters is also explored. Finally, the effect on highly successful fire regimes of the introduction of an unburnable section similar to the fire management tools currently being employed in actual forest fire management.

Methods

Cellular Automata Structure and Update Rule Parameters

The cellular automata was created in Python 2.7 and all figures were created in Matlab R2014a. The cellular automata board consisted of a 40 cell by 40 cell space. The cellular automata board was originally populated with two possible cell types, forest or plain. The board could either be completely forest, completely plain, or a random 50/50 mix of both. These vegetation types represented a trade-off in terms of their ability to catch on fire and their length of burning time (Table 1). These cells could be in one of three states, unburned, burning, or fully burned. In later analysis an unburnable cell type analogous to a fully burned stage and meant to represent a fire line trench used in forest fire management, was randomly added to the cellular automata board.

The cellular automata, in the absence of wind, was updated at each time step with rules applying to a neighborhood size of 8, (Figure 1). Cells on the edge of the board were considered to be adjacent to unburnable or fully burned cells on those edges. For each simulation one cell was lit on fire, the cell was chosen randomly to imitate a lightning strike. The probability of catching on fire is related to the number of neighbors currently burning. With wind there is a small probability of a cell outside of the standard neighborhood in the direction of the wind catching on fire, and a reduction in ignition probability for cells in the opposite direction (Figure 2). This probability increases with each wind level (Table 2). The wind also decreases the probability of the cell Each of the possible wind and vegetation regimes were simulated 200 times to determine the relative effect of wind speed and vegetation type on the overall fire success, or the proportion of cells burned after the cellular automata has run to convergence.

Vegetation Cell Type	Fuel Value (Burning Time in Iterations)	Probability of Catching Fire For Each Burning Neighbor
Forest	5	.07
Plain	3	.1

Table 1: Relative fuel value and ignition probability of the two vegetation types, representing a trade-off between ease of ignition and burning time.

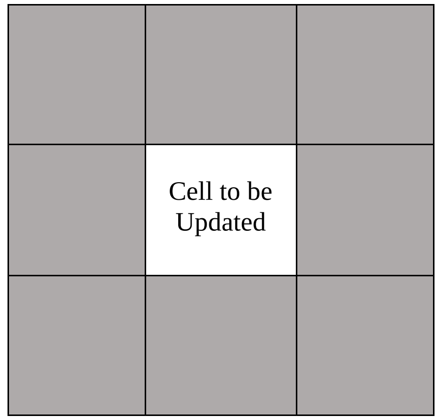

Figure 1: Neighborhood size for each cell in the cellular automata

	Wind Speed			
Change in Ignition Probability	None	Low	Medium	High
Cell One Outside Neighborhood In Wind Direction	0	+ 2%	+3%	+4%
Cell Within Neighborhood From Wind Direction	0	- 1%	-1.5%	-2%

Table 2: Changes in the ignition probability with increasing wind speed with a 50% discount in ignition probability for the within neighborhood cell in the direction the wind is originating from.

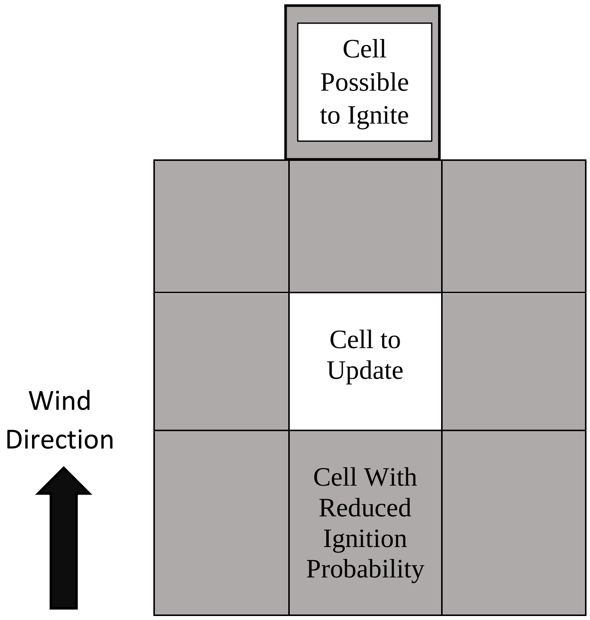

Figure 2: Descriptive model of the neighborhood size for simulations including wind and the alteration in ignition probabilities.

Model Assumptions

In order to address the importance of the trade-off between fuel value and ignition probability this cellular automata simulation model was kept simple and made numerous assumptions. For instance, we assume that ignitions are equally likely to occur anywhere in our cellular automata, this is somewhat similar to what we would expect with a lightning strike but we are ignoring elevation and slope which would affect this, also successful ignition would differ depending on the moisture content, fuel content and vegetation type but this is not assessed. There is also only one ignition site per fire. We do not include any variation of slope or elevation in this model. Also, the region surrounding our cellular automata is unburnable, there is no direct interaction between one edge of the cellular automata and another. The inclusion of wind in our vegetation and wind speed comparisons was not allowed to change direction or speed. With increasing wind there is a probability of the neighborhood size increasing in the direction of the wind, more distant cells can catch on fire from cells outside of their usual neighborhood; however this is only an extension of one cell while this may vary more in real life. Also, grass doesn't have as high a probability of jumping as there are no possibly burning branches to facilitate this jump as seen in actual forest fires but this is not included. Each cell is assumed to be equally affected by all eight immediate neighbors and the probability of ignition is an independent event for each neighbor. Finally, our simulations also ran until convergence, ignoring that in real world forest fire conditions there might be interventions that prevent the fire burning unhindered.

Results

All vegetation regime and wind speed combinations were run at minimum 200 times. The combinations of ignition and fuel parameters were chosen to reflect parameters from previous studies and to maximize complex behavior. At substantially lower or higher ignition probabilities the vast majority of the cells either did not burn or burned completely. Without any variation in burning success it was difficult to assess the relative importance of fuel and ignition probability. In the intermediate ignition probabilities and fuel as shown in Tables (1-2), fuel value has a greater impact on median fire success than ignition ability (Figure 3-4).

Increasing wind speed appears to have a detrimental effect on fire success when there is an equal discount on ignition probability in the direction from which the wind originates as there is an increased probability of the fire jumping outside of its neighborhood in the wind direction (Figure 3). This is most likely an artifact of the wind forcing the fire in one direction which results in the fire hitting the edge of the cellular automata space which is considered unburnable. When the fire hits this unburnable "wall" it will be unlikely to expand back in the direction of the wind due to a discount in that probability leaving only the ability to expand to either side of the wind or the cellular automata edge. Therefore, this effect is likely an artifact of our small cellular automata board and may not be realistic in actual forest fires except in the instances where the fire hits a natural or manmade unburnable barrier.

When the negative effect of wind on ignition probability in the direction the wind is originating from is only half of the increase in ignition probability in the wind direction the inhibitory effect of wind speed on fire success is less marked. In this case there may be an advantage to low or medium wind speeds in overall fire propagation (Figure 4). Varying advantage to wind for fire success also seen in situations with extremely low ignition probability outside of our general parameter space of interest (Figures 7-8).

The addition of a randomly placed 1 by 40 strip of unburnable cells to the model to simulate a fireline trench, a common fire containment technique, resulting in very large reductions in fire success (Figure 6). Due to the ability of the fire to jump under windy conditions, this reduction was less significant in high wind conditions (Figure 6).

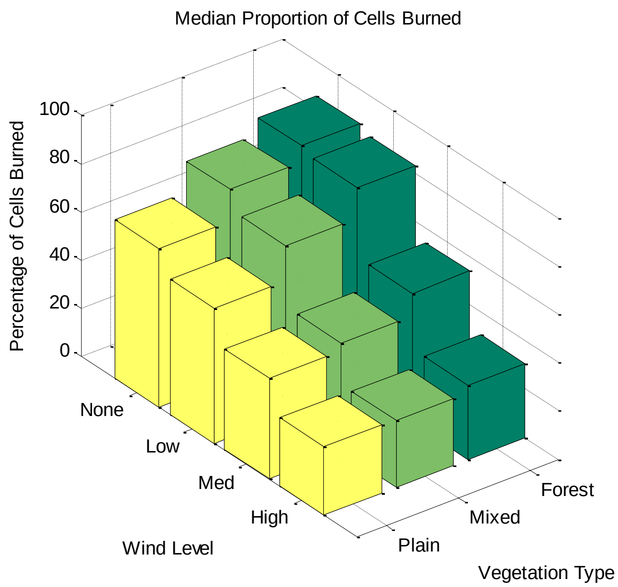

Figure 3: Percentage of cells burned for each vegetation and wind level combinations for wind regime with equal increase in probability of fire jumping and discount in ignition probability in the direction from which the wind originates.

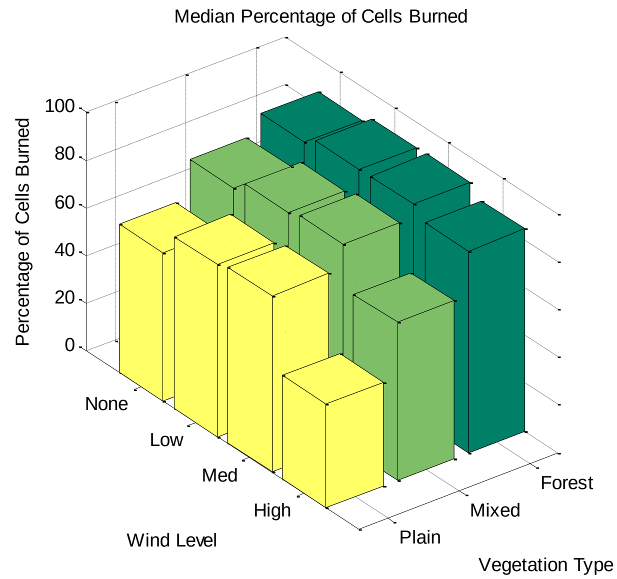

Figure 4: Percentage of cells burned for each vegetation and wind level combinations for wind regime with the discount in ignition probability in the direction from which the wind originates half of the increase in probability of expanded ignition in the wind direction.

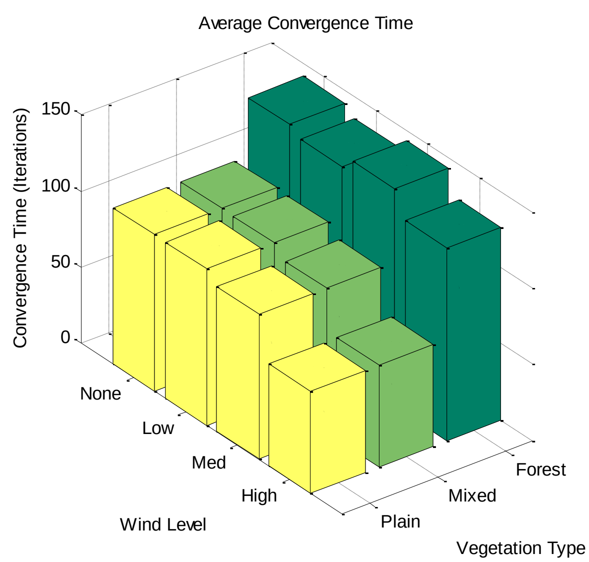

Figure 5: Variation in convergence time among vegetation and wind combinations for simulations with a discount in ignition probability equal to 50% of the increase in ignition probability for increased neighborhood size with wind.

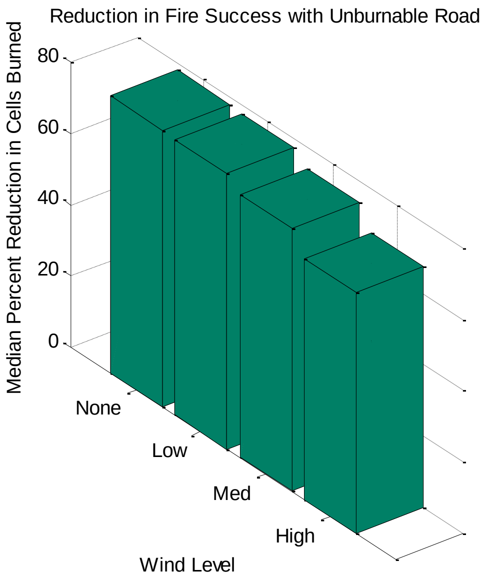

Figure 6: Reduction in median cells burned with the random addition of unburnable strip of cells.

Sensitivity Analyses

The simulations appear to be very sensitive to initial conditions. In particular our analysis focused on the ignition probabilities as these were chosen due with respect to fire simulation behavior rather than fuel value ratios which are more established in the literature. The final fire success changed drastically with respect to the ignition probability per neighbor for both the plains and forest vegetation regimes (Figures 7 – 8). However, this effect was heavily influenced by wind speed, as low and medium wind speeds appeared to be beneficial for fire success under certain ignition probability scenarios (Figures 7 –8).

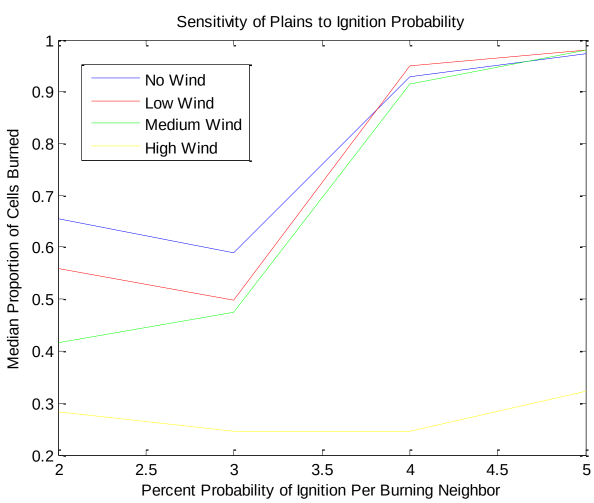

Figure 7: Sensitivity of fire success for plains type vegetation to changes in ignition probability

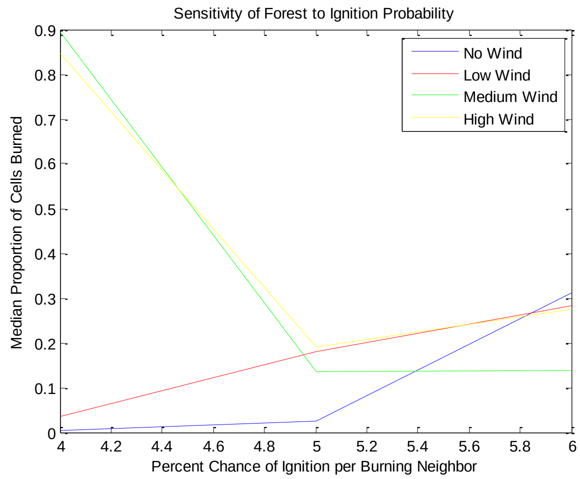

Figure 8: Sensitivity of fire success for forest type vegetation to changes in ignition probability

Discussion

This cellular automata forest fire framework while simple is still reveals complex behavior. It is also generalizable which would allow it to be adapted to various vegetation regime scenarios. However, its simplicity does mean that it ignores detail included in other forest fire behavior models. In particular this model does not include slope or elevation which have been known to drastically alter the probability of ignition by outside sources such as lightning strikes and fire behavior. Also, fire can interact with its environment in more nuanced ways, creating micro-climates where heat from larger fire clusters may increase the ignition of nearby areas and could change or alter wind patterns depending on heat production.

The cellular automata does begin to address the trade-off between fuel and moisture content that can be present in areas prone to forest fires, either in the interface between forest and grass or shrubs or between understory and canopy vegetation. This trade-off is analogous to moisture and woody mass content in vegetation. In the parameter space we explore fuel value appears to have a greater impact than ignition probability on final fire success. However, our ignition probabilities were very similar, and our crude sensitivity analyses indicate that even minimal changes in ignition probabilities can have significant impact on fire success. In real world situations there may be an even greater disparity between vegetation types in terms of fuel value and ease of ignition.

Wind speed and direction often have a large impact on forest fire spread and in our simulations this was especially significant as there was an unburnable edge to our cellular automata which may be analogous to a natural or manmade barrier or the interface between quickly burning vegetation and vegetation more resistant to ignition. It is possible that a larger increase in neighborhood size or the ability of the wind to change direction would alter this relationship. Furthermore, high winds are sometimes able to extinguish small fires, a penalty we did not include in this model.

As a reduction in fire success with the random addition of an unburnable section was seen in these simulations a similar strategy could be used in fire management. If an actual forest area was simulated the theoretical effect of fireline trenches in various regions of the forest with randomly occurring ignition areas could be determined, even under varying wind conditions.

Overall, this model begins to address the trade-off between fuel value and ignition ability that may be very important in regions of interface between various vegetation regimes.

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