CONTROL AND SPREAD OF WILDFIRES II

New Mexico

Supercomputing Challenge

Final Report

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Problem Explanation

This year we are expanding upon last year's project on the control and spread of wildfires. Fire has been a very important part of our lives and will continue to be so in the future, in both positive and negative ways. Wildfires cause extensive amounts of life and property damage; and we wanted to know the best way to extinguish a fire in progress and the best way to protect property from an out of control blaze.

Last year we created a model of a fire on a flat plain. We included the variables of fuel load, wind speed, wind direction, and moisture content. We then took our model to the local fire department and were able to accurately model a fire that they recently fought, verifying the reliability of our model.

This year, we have added a third dimension to our model, topography. On the Llano Estacado this variable did not affect our model much, however, in most other parts of the world it can be the most prominent factor affecting the fire's behavior. We then had to develop a procedure to cause the wind to react to the topography. Firefighters who try to fight the fire and protect a residential area were also incorporated into the model. Then we tested various firebreaks to determine which design is the most effective in diverting or slowing a fire's progress.

Solving the Problem

Last year we began our model in "StarLogo TNG," an agent based model. We did have plans to expand our modeling this year into "NetLogo" (a more advanced and versatile modeling program), however due to time constraints and limiting our project to goals to those that we could achieve in one year, we simply expanded our old model. This was, as we found out, not a detriment to this year's project goals. With StarLogo TNG, we can set up different types of fire breaks easier and more quickly than we could with NetLogo, as we understand the language.

We solve the various problems by introducing an agent in "SpaceLand" (The area where the agents will operate) that will consume fuel and multiply and progress in accordance to the following variables:

Fuel Load—The amount of fuel available per square area of land. This represents different vegetation types and densities. This will be represented in our model by a scale of 1-10 in shades of green. The darker the green, the greater the fuel load. The fuel load in an area can change greatly, on one side of the fence there can be a green wheat field which has an extremely low fuel load, and on the other side of the fence, there can be land enrolled in CRP (Conservation Reserve Program) which can have a very high fuel load. The fuel load in a single pasture can change too, depending on what kind of grass grows from place to place and the quality of the soil across a field. The fuel loads that we will use for our model will be:

1) Very, very low—less than 200 pounds of fuel per acre

2) Very low—from 200-500 pounds of fuel per acre

3) Moderately low—from 500-800 pounds of fuel per acre

4) Moderate—from 800-1100 pounds of fuel per acre

5) Moderately high—from 1100-1500 pounds of fuel per acre

6) Very high—over 1500 pounds of fuel per acre

Moisture Content—The amount of moisture in the area. Often the land will be very dry before a thunder storm, therefore, lightning can easily start a fire. As the storm progresses it may rain, increasing the moisture, retarding the fire's progress, and possibly even putting the fire out. This variable can also represent the growing stage of the vegetation represented.

Wind Direction—Wind direction plays a vital role in fire behavior and control. If there is a wild fire, the fire fighters may have had it under control or could have had a firebreak set up ahead of it, but if the fire suddenly changes direction, it may become uncontrolled once again.

Wind Speed—Wind speed is also very important in fires. A fire under a light wind might not ordinarily cross a firebreak or obstacle such as a road, but if the wind were blowing enough, the road would barely slow down a raging fire. We will use these numbers to represent the different wind speeds:

0—0-3 mph

1—3-10 mph

2—10-15 mph

3—15-25 mph

4—over 25 mph

Topography—The heat that radiates from a fire tends to rise, therefore a fire will advance much more quickly up a hill than down a hill. The wind will also be affected by the terrain. A hill can provide a wind break on one side and channel wind down a canyon on the other side of the hill, thus changing wind speeds and directions. We control this variable with “StarLogo TNG’s” versatile terrain editor.

With control of these variables in our model, we will “start a fire” on the map and let it burn until the entire map is consumed or the fire burns itself out. We can then alter the map by adding a firebreak and running the model again.

Our model runs on these basic principles:

1) Burn

a) Test to see if patch color is some shade of green

b) If so, then add one shade of white to the patch.

c) If not, then test to see if patch is already burned

i) If so, then have a 66% chance of dying (This gives a fire a chance at crossing a firebreak with sparks and tumbleweeds).

ii) If not, then have a 66% chance of dying.

(The 66% was determined through trial and error relying on local firefighter’s experience of fire behavior.)

2) Spread

a) Test to see if a random number between 0-100 is less than or equal to dryness.

b) If so, then choose a random number between 0-360 for a direction

i) Then create a new fire and send it 1 step in the chosen direction.

3) Wind

a) Select a random number between 0-45 and add it to the wind direction

b) Then divide wind speed by 2 and add 0.5 and take that many steps in the chosen direction.

4) Hills

a) Test if patch height is less than patch height ahead.

i) If so, then go forward the difference between patch height and patch height ahead times 4.

ii) Hatch

b) Test if patch height is greater than patch height ahead.

i) If so, then go back the difference between the patch height ahead and patch height times 1.

ii) Have a 50% chance of dying.

Mathematical Model

The mathematical formulas that our model follows are stated below.

Setup

F_1 = first fire agent generated

F_1 is randomly placed on an x y grid according to …

$x \sim U[-50.5,50.5)$

$y \sim U[-50.5,50.5)$

Where U is uniform distribution.

F_1 is randomly placed on a "patch".

A "patch" is an area that is centered on an x y grid where x_0, y_0 ε $\mathbb{Z}$

A "patch" includes…

$x \; \varepsilon \; [x_0 -0.5, x_0 \, 0.5)$

$y \; \varepsilon \; [y_0 -0.5, y_0 \, 0.5)$

Spread

f_i = fire agent i

t = time

P = probability

The probability that a fire sparks another fire is …

$P(f_i \text{ produces } f_j), [t,t+1)$

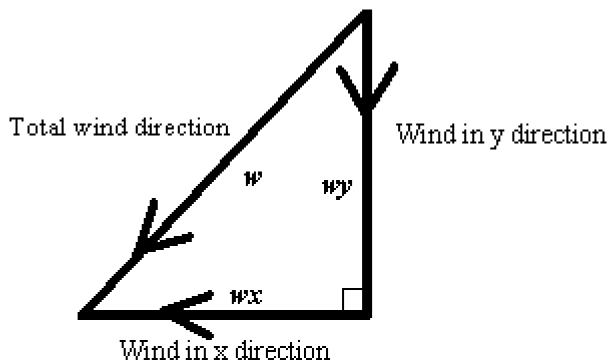
The location of f_j is…

$x_j = x_i + cos\theta r + \boldsymbol{wx}$

$y_j = y_i + \sin\theta r + \boldsymbol{wy}$

Where "θr" is a random angle uniformly distributed on $[0,2\pi)$

Where "$\boldsymbol{w}$" is a wind vector composed of x and y directions



Burn

L_k = fuel level in "patch" K

The fuel level decreases by the number of "fires" on that "patch"

$L_{kt+1} = max(L_{kt} - n, 0)$

Where "n" is the number of fire on "patch K"

If $L_{kt} = 0$, all agents on "patch K" "die", in the time interval, $(t, t+1]$

Hills

If there is a positive grade

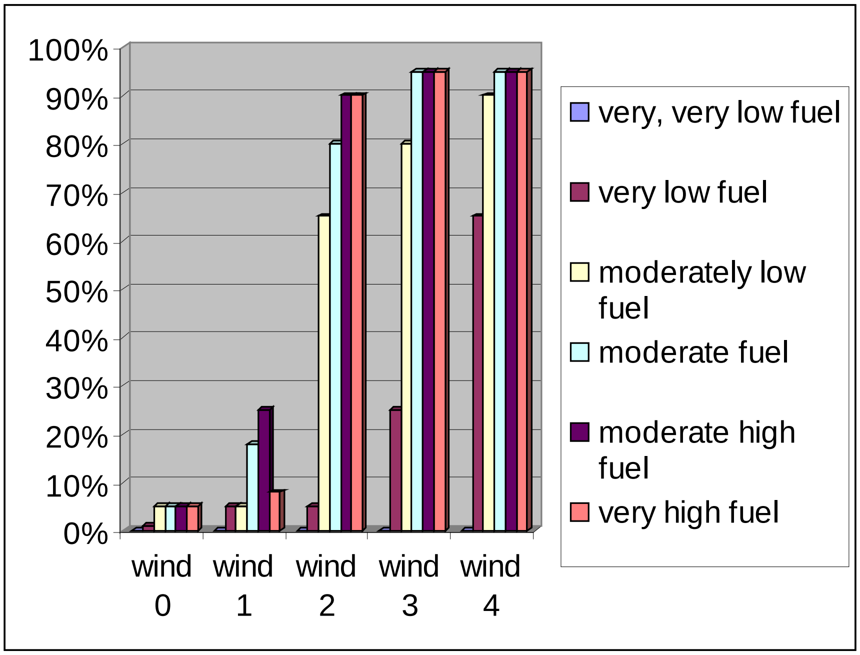
F_1 moves forward (marginal difference)(4)

If there is a negative grade

F_1 moves backwards (marginal difference)(1)

Last Year's Results

Last year we were able to accurately model a fire and did a lot of work with roads and how the fire reacted to them. We used county roads as our standard. We started with the fire approaching a road at a perpendicular angle. We tested this under varying fuel loads and wind speeds and directions. The following graph shows the percent chance that the fire has of crossing the road under the specific conditions.



We did not give anything a 0% chance or a 100% chance as there is a lot of random numbers and anything could happen if the model were run enough times.

We also tested the impact of varying fuel loads in drainage ditches that usually run next to roads. They can either have higher fuel, due to being able to receive larger amounts of runoff, or they can have a lower fuel load from the state or county mowing it off. We found that under conditions in which a fire didn't usually cross, the fire was able to cross the road if the ditch contained a high fuel load. On the other hand if the ditch had a lower fuel load, it did delay the fire's crossing significantly.

Another factor that we tested, was whether or not the fire's angle of approach to the road affected its chance of crossing the road. We found that the lower the fire's angle in comparison to the road, the less chance it had of crossing over the road. This was due to the fire traveling with the road instead of against it. We used this information in the development of our firebreaks.

Our Goals

This year we decided to use the model that we created last year to find the best ways to slow, stop, or divert a fire with firebreaks, as well as to find the most effective way for the firemen to work with the firebreak to get the fire under control and extinguished thereby saving lives and property. With StarLogo TNG, it is easy to manipulate the terrain for different scenarios, and set up different types of firebreaks for testing.

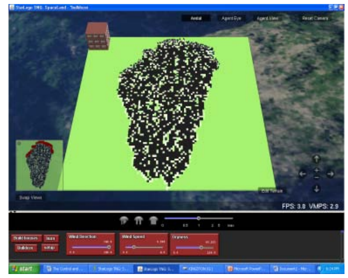
This Year's Results

Last year we developed a model that accurately portrays how a fire will act under certain variables and verified that our model is viable. This year we modeled various situations and fire breaks so that we would be able to see how the fire would act under the given situation. We tested two fuel loads in the different firebreak designs. We determined firefighter's ability with each fire break design to protect property by counting how many houses were left at the end of each test. We further pursued the fire's advancing angle to the firebreak.

Fire Men

This year we added firefighters to our model. We set up independent agents to search for and put out the fire. Currently we have a few firemen with fire extinguishers killing individual fire agents when there can possibly be thousands of fire agents so, our fire fighters can easily be overwhelmed. However, this is a great step towards setting up a program that would test firefighting methods previously impractical due to safety hazards. This is also getting us closer to another important piece of information, how much water will it take to put the fire out? As fire trucks can only carry a limited amount of water it would be a great benefit for the fire fighters to know how much water or fire fighting agent is needed to extinguish a fire under various conditions.

Right now though, our firemen aspect of the model shows how important early fire control is and how little effort is needed to put a small fire out before it gets out of control. In this model we have a village placed in the way of a fire. The wind is about 10 mph with damp conditions and a low fuel load.

As you can see, the fire was able to build up and envelope the village. In the next model we let 10 firemen find the fire and proceed to try to put it out.

In this model the firemen were able to find the fire and put it out before it had a chance to grow. The firemen were able to save the village from the fire.

We have also found that if an area is in danger, it works best if the firefighters "stage" in front of it, however, they can't be too close or too far away, because if they are too close they do not have time to successfully engage the fire. However, if they are too far away, the firemen's resources are too dispersed to protect the village if the fire gets by them.

Fire Breaks

We tested several different types of firebreaks to learn which one would be the most effective in diverting a fire or slowing it. We tested various shapes and fuel loads for the firebreaks, as well as fire direction in relation to the position of the firebreak. We also tested whether the break slowed the fire enough for the firemen to extinguish it. We measured the firebreak's effectiveness by placing nine houses in front of the fire to represent a village, and recorded how many houses survived the fire.

One of the things that we took into account when we designed the firebreaks was feasibility and aesthetics. For example, you could create a very effective firebreak for your house by plowing up all the vegetation and converting it to mineral soil all around your property for one hundred yards in all directions. This would pose a few problems for the people living in that residence. It would probably be very dusty and the plowed up area would be subject to wind erosion, removing the topsoil from the area. It would not look very good to have a huge brown square all around your house either. So, we tried to keep the fire breaks to areas of low fuel or small areas of no fuel.

To analyze our results more accurately we used Microsoft Excel's statistical functions. Since we only ran each model 10 times, we used small sample inference and the Student's t test (which our mentor found appropriate). The equation for Student's t is as follows:

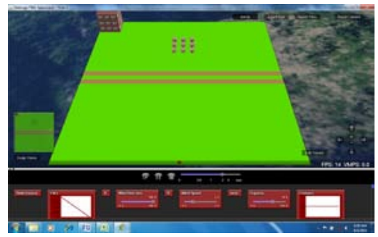
$$t = \frac{\bar{Y} - \mu}{S/n^{1/2}} = \frac{\bar{Y} - \mu}{S_{\bar{Y}}}$$

We used the Student's t to determine how different our data sets were. In this case how the firebreak's effectiveness compared to a control of no firebreak. We also used this function to determine if one design was significantly better than others.

We tested the following fire breaks under these conditions. The moisture content was set at 40%, the wind speed was at a 1 or between 3 and 10 mph, the wind direction was blowing the fire directly at the village, the base fuel load was moderate, the village consisted of nine houses arranged in a block, and firefighters were extinguishing the fire. We started with no firebreak and then added different designs: two strips of no fuel, two strips of low fuel, a solid strip of low fuel, and an arrow or V shape around the village. However, StarLogo TNG does not allow us to draw a homogenous diagonal line. This reduced the effectiveness of our angled breaks.

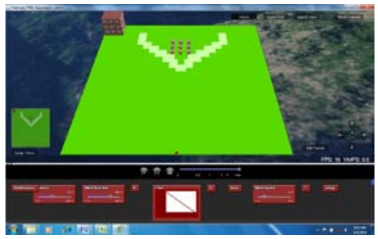
Control, no firebreak

Two Lines, low fuel



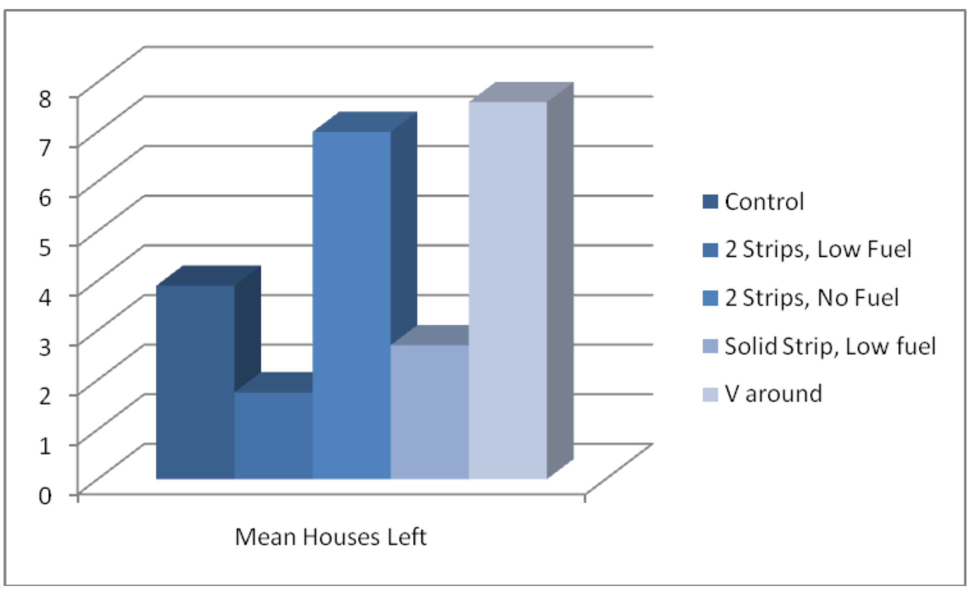
Two Lines, no fuel

Single Line, low fuel



V design, low fuel

The following graph shows the average number of houses that survived the fire after running each model 10 times.



From the information presented in the graph we were able to infer a couple of things. First of all, we were surprised to find that not all firebreaks were helpful. Next we found that a firebreak that was more effectively designed with low fuel was better than a straight firebreak with no fuel. When we noticed the first problem, we ran our model more times and examined the behavior more closely. The reasons the firebreaks seemed to be detrimental was that the firebreak was actually doing its job, it was slowing the fire down as indicated by our fire population graph, but it was also widening the head of the fire spreading the firefighters resources out too thinly to stop the fire's progression.

To more accurately determine the differences between the breaks we have run a t-test on the above sets of data testing the control against the firebreaks and testing the best firebreak against the others. The following table shows the result of the t-test.

Firebreak	control	2 Strips, Low Fuel	2 Strips, No Fuel	Solid Strip, Low Fuel	V Around
T-test (Rounded to 2 decimal places)	1	0.13	0.06	0.45	0.02
	0.02	0.00	0.60	0.00	1

These numbers show that the V around and the two strips of no fuel were significantly better than the control. The test also showed us that the V around is not significantly better than the two strips of no fuel. There is strong evidence, 87%, that the two strips of low fuel were detrimental to the survival of the town. Since we were very surprised by these results, we doubled our sample size and nothing changed.

We can also deduct that an effectively designed and placed firebreak is better than just an ordinary straight line. From the graph we can tell that the V design saved, on average, more houses than the next best firebreak, the two lines with no fuel. From the statistical analysis, however, we see that there is only a 40% chance that it is a significantly better firebreak. These chances are not good enough for us to draw an immediate conclusion (for us to do so we will have to do a significant amount of more testing), but right now, we will give the upper hand to the V break due to erosion problems and aesthetics mentioned earlier.

Here, we have the fire break that performed the most desirably, the V, or arrow shaped pointing in the direction that the fire is coming from, and surrounds the town. It has moderate fuel load, with the break made of very low fuel.

The fire men staged just to the houses side of the fire break, and were able to stop the fire, and save all of the houses. We then ran this model by placing the houses on the top of a hill and by placing the houses in the bottom of a low spot with and without the V break. In both cases we found that a firebreak was better than no firebreak.

The firebreak's angle to the direction of the fire was also tested. However, due to limitations in the program, we were not able to model this as accurately as we wished we could have. But we did strengthen several beliefs about the fire's behavior. First of all, the fire has more difficulty in crossing a break when it is running at an angle to it or with it. This helps explain why diagonally shaped fire breaks work the best at diverting a fire away from the village. An area with no fuel is a better break than an area with low fuel. Firefighters are better extinguishing agents than simply a firebreak. The firefighters need to effectively stage the fire or use the firebreak to their best advantage. Such as, the firebreak is not as helpful if the firefighters go out in front of it, because if the fire gets past them, then they are stuck behind the fire. The firebreak is also not as effective if the firefighters are too far behind it, because it has had time to increase to its original intensity.

<u>Distractions</u>

While working with our firemen and firebreaks we have discovered a very interesting result of having them together. In one model the firemen were to stay behind the firebreak and let the firebreak slow the fire down so it was easier to put out. However, when the fire crossed the break in one place, all of the firemen ran to put it out. While the firemen "had their backs turned," you could say, the fire would cross the break behind them and would destroy the village before the firemen could do anything about it. This usually occurred with a relatively strong fire break as well, and we were very surprised to find that it did not work as well with the firefighters as we anticipated. We have heard that at some real fires all of the firemen would run up to the largest part of the fire to put it out, while, unbeknownst to them, the fire is threatening a residence elsewhere. This shows how it is important to have a chain of command in the field with someone directing the firemen and trucks.

Firefighting Techniques

While testing firebreaks we also discovered some firefighting tactics that are effective in diverting the fire away from residential areas or other locations of interest. These can change according to from which direction the fire is approaching. When the fire is coming straight at a village it can be more effective to wait for the fire to get close to the village, then concentrate all firefighting resources at one point in front of the fire. This will split the fire in two and allow the firefighters to work on the inside flank of the fire and push it around the village.

However, if the fire is approaching at an angle to the village, we would suggest that the firefighters stage near the village on one flank of the fire; this would push the fire around one side of the village. The firefighters could then work on putting the rest of the fire out when the village is safe.

Executive Summary

This year, we improved upon last year's wildfire model by inputting topography, which is very important for some areas. We were able to get the wind to react to the topography, because wind can funnel through canyons, and hills or mountains can act as wind breaks. This was the most difficult to simulate. We also implemented firemen, one of the most crucial resources that a community has in protecting lives and property.

We used our more advanced model to test different varieties of firebreaks and fire fighting tactics. We found that out of the firebreaks that we tested, a V-shaped firebreak with the village inside of it was the most effective. We also found through further testing, that firebreaks are more effective if they are placed at an angle to the fire's advancing direction. The firemen perform best if they stage just behind the firebreak, and put it out as it is trying to cross. Not all firebreaks are helpful; the firebreak has to influence the fire in such a way as to give the firemen a strategic advantage. Firefighters in the field need a chain of command and a common goal to help organize them so they will be able to use their resources more effectively.

By expanding our model this year, we have tested the limits of StarLogo TNG. It has been a very effective tool in verifying our procedures and models. However, it is now starting to limit us. We cannot import real topographical maps from outside sources, we have a limited amount of space in SpaceLand, and we cannot build custom procedures. There is also a limit to the number of agents that can be in SpaceLand at once. This may be a moot point since we seem to have reached the limits of our PC. Sometimes so many agents were running so many procedures, that the program would become confused and would either shut off entirely or mix up breeds of agents and the procedures that they were supposed to follow. To continue this project we need to change our modeling program to enable us to overcome these obstacles and to eventually meet the goal of creating a marketable program to be used by fire departments, cities, and individuals to develop more effective firefighting techniques or just how to most effectively protect their own home by custom designing firebreaks to meet an individual's needs.

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