The Impact of Forest Fires on Water Resources

New Mexico

Supercomputing Challenge

Final Report

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Team 2

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1.0 Executive Summary

We intend to investigate the impacts that forest fires can have on the water resources of forest environments that human populations are dependent on. Apart from the general environmental disruption caused by forest fires, human water sources can be contaminated or otherwise compromised. For example, forest fires dramatically change the land cover of an area, lending to concerns about flash flooding, erosion and water quality. Based on factors such as tree density, moisture, land slope and weather, different forest types are more susceptible to damaging forest fires than others. The model is in Netlogo.

The model was model was created with a cellular automata, empirical method and incorporates several factors such as wind, elevation, and fuel type to in an attempt to accurately portray how a forest fire spreads. The model makes basic assumptions about the likelihood of given patches igniting based on established, empirical observations (for example; a fire burns longer with more fuel, it is suppressed by moisture, it is biased by air currents factors like wind and elevation). The model also incorporates GIS elevation data of various landscapes, including the region where the Pacheco Canyon fire burned in the summer of 2011. A final aspect of the project examined the optimization of firefighting tactics within our model.

Throughout the course of this project we collected field data and data from our model. The fieldwork was done in the regions burned by the Pacheco fire: water samples were analyzed and the landscape was observed. Many experiments were conducted within the model, including tests on the variables of windspeed, elevation, moisture and fuel density. Data was collected about the area burned and the debris levels of bodies of water.

The model was tested against the behavior of the Pacheco fire, and will not precise it did follow similar patterns. The data from this model illustrated a strong impact of windspeeds and elevation profiles upon debris levels.

2.0 Background

Dry weather and drought convert green vegetation into dry, flammable fuel; strong winds spread fire quickly over land; warm temperatures encourage combustion. When fuel, oxygen, and heat are all present, all that is needed is a spark to ignite a blaze that could last for weeks and possibly destroy acres of woodlands.

On average, more than 100,000 wildfires, also called wildland fires or forest fires, clear 4 million to 5 million acres of land in the U.S. every year. In recent years, wildfires have burned up to 9 million acres of land per year. A wildfire moves at speeds of up to 14 miles an hour, consuming everything in its path.

2.1 Impact of a Fire on an ecosystem

A forest fire is a dynamic, predictable, yet still uncertain, natural process. A forest fire can have numerous positive and negative effects on an ecosystem. It is important to balance these effects properly in order to ensure a sustainable ecosystem. Forest fires have the potential to have a tremendous impact on the water resources of an ecosystem. The impacts are various interrelated mechanisms including effects on soil chemistry, soil physical properties, soil biological response, the hydrological cycle and water quality. As illustrated in figure 1 (below), all of these systems are highly complex, tying together the physical, biological and chemical aspects of an ecosystem as well as the properties of its upper and lower ground layers.

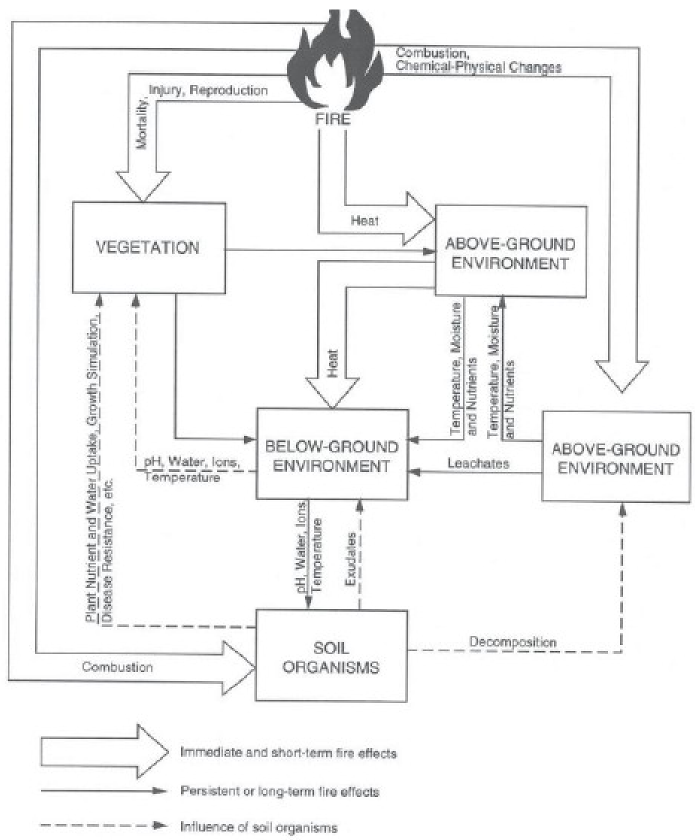


figure 1: Immediate and long-term responses to forest fires

2.2 Describing and Quantifying Fires

To begin quantifying and modeling these impacts, it is necessary to start defining different types of fire and their potential impacts on an ecosystem. A broad way of defining the role of a fire within an environment is through defining a particular *fire regime*. This is useful for examining the role of fires within certain vegetation types, especially the likelihood of land types to have certain fire types. The fire regime types are as follows:

- *Understory fire regime*: A regime type that is most likely to have a fire type that is considered non-lethal and in which about 80% of the vegetation survives the fire and the vegetation type remains fairly unchanged. It applies to vegetation types which include many fire resistant wood types.
- *Stand replacement fire regime*: This regime type has the potential to have a fire which is lethal to the majority of the vegetation where about 80% dies off as a result of the fire. It applies to fire susceptible forests, woodlands, shrublands and grasslands.
- *Mixed fire regime*: A regime which supports fires whose severity varies between lethal stand replacement and non-lethal understory. This is the most common type as temporal and spatial variation in parts of an ecosystem often results in a wide disparity of potential impact.
- *Non-fire regime*: A landscape type in which a fire is not at all likely to occur.

Another important aspect to be addressed when trying to quantify the impact of a fire is a measure of the magnitude of the fire, specifically the intensity or severity of it. Intensity and severity are defined as two different aspects of fire measurement with different values for assessing impacts of fires.

Intensity refers to a measurement of the rate of heat released from a fire. A quantifiable measure of intensity comes from an equation known as Byram's definition of fireline intensity. Byram's equation is as follows;

$$\mathbf{I=Hwr}$$

Where *I* is the intensity of the fireline (the front of the fire and measured in kW/m/s), *H* is the heat yield value of the fuel source (in kW/kg), *w* is the mass of the fuel consumed (in kg/m2) and *r* is the rate at which the fire is spreading (in m/s) (also known as the Fire Behavior).

The measurement of fire intensity is useful in predicting the extent and magnitude of a burn. For example, intensity has been shown to be directly proportional to flame length, and flame length is used for predicting possible damage a fire may inflict on buildings. The *depth of burn* of a fire is the measure of how deeply the fire burned or how deeply lethal levels of heat reached into the organic soil horizon (the layer of soil that includes the majority of plant and other biological matter). Depth of burn is the main factor of importance when determining the impact on soil and water resources. It relates to the amount of bare mineral soil exposed to erosion, the depth at which chemical changes may occur and the microbial populations which may be affected. It is important for examining how erodible land becomes and how hydrological recovery process is changed. Another types of fire measurement is *Severity,* which differs from intensity in that it is concerned with above and below ground heat pulses. It is the concept which relates intensity and depth of burn. Severity incorporates a two-dimensional quantification of fire magnitude, accounting for both above- and below-ground heat level.

2.3 Impact on Water Resources

Forest fires can impact water resources in several different ways. Fires can shower water sources with debris. This extra sediment can slow or damage water filtration processes and increase the resources needed to produce clean drinking water (Meixner and Wohlgemuth, 24). The debris can also change the chemical makeup of the water. For example, large amounts of ash and burned material have been shown to raise nutrient levels, especially phosphorus and nitrogen (Meixner and Wohlgemuth, 25).

It is also an observed phenomena that forest fires are often be responsible for increased watershed response, namely flooding and mudslides. These natural occurrences are threatening to human safety, and can disrupt water resources by, for example, wiping out a dam. This relationship between fire severity and erosion potential is demonstrated in Illustration 2, which shows the relationship between fire severity and the magnitude of watershed response. Essentially the graph shows that as fires become more severe (that is to say, they become more intense and have a higher depth of burn) and time passes, the potential for a large scale watershed response becomes greater. Studies in the Santa Monica mountains have found that erosion rates in a burned watershed can be up to 50-100 % greater than a vegetated one. Forest fires can also have the impact of creating a larger amount of so-called 'hydrophobic soils', a soil type that becomes impermeable to water, preventing it from soaking in and causing the vital resource to simply slide off the surface (Ainsworth and Doss).

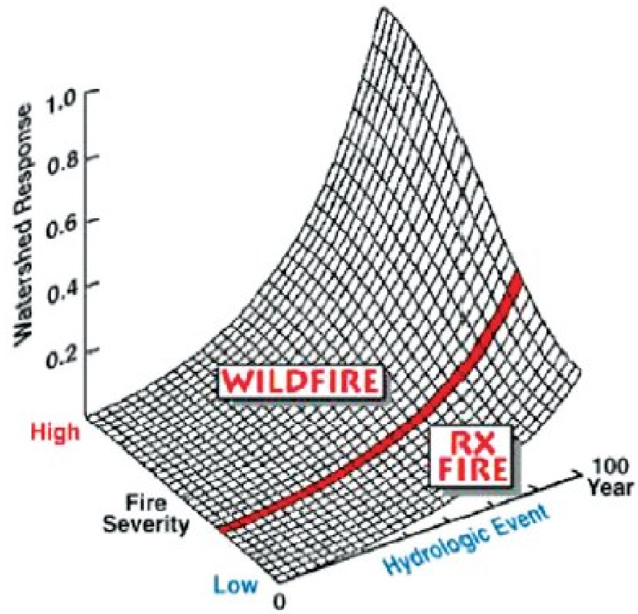


Illustration 1: An approximation of the magnitude and the timing of watershed response to fires of varying severity, including wildfire and the lower section corresponding to prescribed burns (Neary, Ryan and DeBano, 16).

2.4 Firefighting Techniques

When a forest fire is spotted, teams are immediately dispatched to fight the flames. The first thing they do, when available, is to establish a fire line. They do this by removing all vegetation (fuel) that could assist the fire. This is an attempt to allow the fire to die out slowly before it reaches any other fuel sources. After cutting off the fuel, firefighters must use tools such as shovels, picks, chainsaws, and hoses to prevent the fire from spreading further.

3.0 Fieldwork

By looking at real world data, we can incorporate more realistic parameters into our model for better results. We are examining one major fire that happened recently: the Pacheco Canyon Fire. We determined phosphate levels in the surrounding water sources.

Picture 1: A picture taken showing the Nambe River drainage at a region burned in the Pacheco Canyon Fire.

3.1 Pacheco Canyon Fire

On June 18th, 2011, a wildfire started in the Santa Fe National Forest, about 9 miles north of the city of Santa Fe. The fire burned an estimated 10,250 acres in about 10 days, primarily in the Nambe River drainage, as seen in *Map 1*. As part of the background research for the modeling and analysis of our subject, we decided to collect field data about this particular fire. The primary analysis shows how the fire affected the water quality in the Nambe River and other small rivers approximately four months later.

The water samples (see *Picture 2*) were obtained on October 9th and 10th 2011, 3.5 months after the fire. They were collected from four separate locations. Two samples were collected from two upper sections of the Nambe River at points upstream of the burned regions (Samples A and B), and two samples were collected from water sources downstream of the burned region, one from the main Nambe River (Sample D) and other from the Rio Capulin (Sample C).

There were immediately clear distinctions between the water samples collected upstream of the fire as opposed to those which would have flowed through burned regions. Judging from the appearance, the water from upstream was very clear and had little to no visible particulate matter. Samples C and D were very cloudy and dark with comparatively large quantities of particulate matter.

Chemical analysis was performed on the water samples in the form of a test for phosphate levels. Phosphate is often observed to appear in elevated levels in water after forest fires, and is attributed to ash and other debris being washed into the water due to erosion. Elevated phosphate levels can cause growth explosions in aquatic plants, which subsequently leads to reduced oxygen levels, making water uninhabitable for aquatic organisms.

3.2 Determination of Phosphates in Water Samples

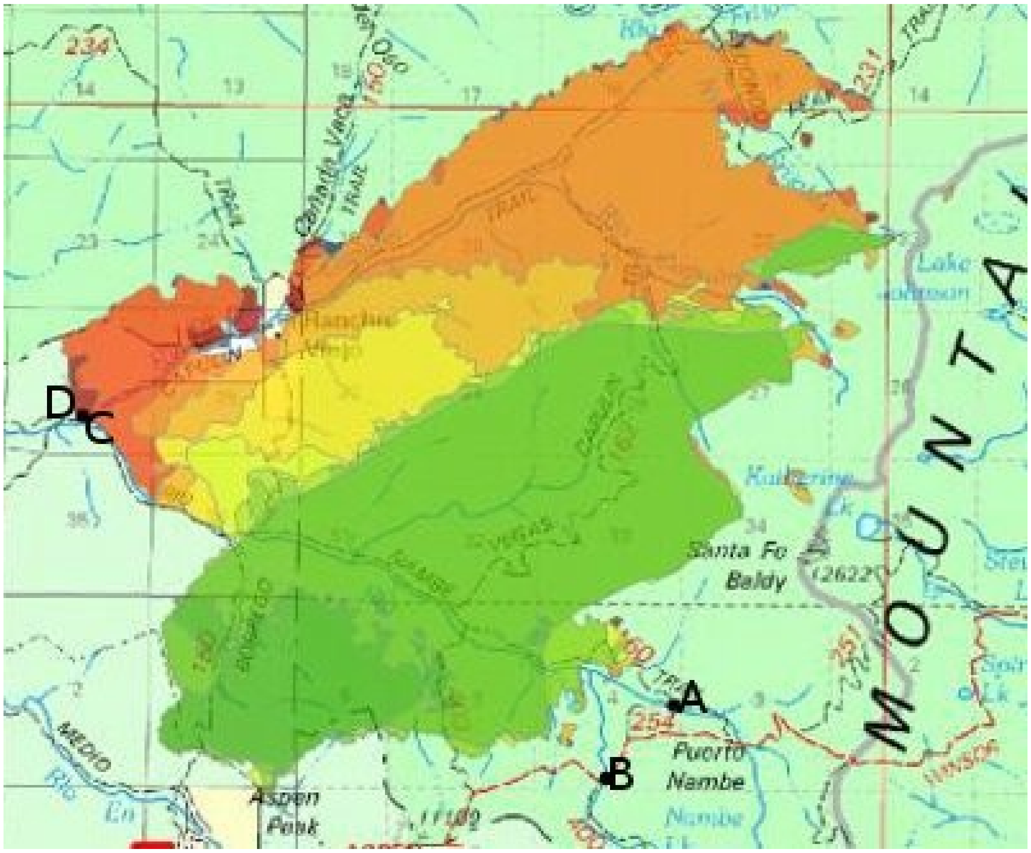
The basis of this experiment is to add a reagent to the water samples; it reacts with any phosphates present causing them to be visible as blue precipitates. A standard is created where this reagent is mixed with a water with a known quantity of phosphate. This standard makes it possible to estimate the concentrations in the samples being tested (Schumann).

The reagent is composed of the following:

- 50mL H_2SO_4 solution
- 5mL potassium antimonyl tartrate ($K(SbO)C_4H_4O_6 \cdot 0.5H_2O$) solution
- 15ml ammonium paramolybdate $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$) solution
- 30mL ascorbic acid solution

The standard solution is composed of distilled water and potassium phosphate dibasic (KH_2PO_4), they are adequately diluted to make solutions with phosphorous concentrations of

Map 1: The burned region of the Pacheco Canyon fire. The shading represents progression over time. Sample locations A, B, C, and D are also labeled.



10, 5, 2.5, 1, 0.5, 0.2, 0.1 and 0 ppm. 25 drops of each solution are placed in a well culture plate and then 4 drops of the reagent are added to each well. As expected, there was a clear trend of darker blue in the solutions of the highest concentrations, those with little phosphorus were almost clear and the solution with no phosphorus was completely clear. Next four samples of 25 drops each are taken from each water sample (A, B, C and D) and placed in a 16 well culture plate (taking four samples from each sample is designed to minimize random error) and four drops of the reagent is added to each well.

After the reagent was added, samples A and B remained quite clear and Samples D and C turned a faint blue. D and C were not as dark as the standards of 10, 5, 2.5 or 1 ppm, but appeared to be fall somewhere between 0.5 and 0.2 ppm. These results of this test indicate that the samples taken from rivers that flowed through burned areas acquired measurably higher levels of phosphorus than those that were not exposed to fire debris.

There are certain sources of error associated with this experiment, an important one being that this test was not performed until several weeks after the water samples were collected. It is possible that the prolonged storage in containers could have changed the water chemistry. However, all the samples were stored identically, so any change would have affected them all equally. Another source of error was that the comparison of the water colors was purely observational. This was somewhat accounted for by having two different people unfamiliar with the experiment examine the samples (their observation correlated with those expressed previously). However, this subjectivity could further be improved upon by taking pictures of the standard and samples and using software to more accurately compare the colors.

Picture 2The four water samples taken from various locations upstream and downstream of the Pacheco Canyon fire. Starting at upper left and moving clockwise, they came from the Rio Capulin (C), the upper Nambe River (A, from Puerto Nambe), the upper Nambe (B, from Nambe Lake), and the lower Nambe (D).

However, taking all the errors into account, it can still be reasonably asserted that there was certainly a difference in the phosphorus levels between the samples, with those that were taken downstream of the burned region having measurably higher amounts. This correlates with our predictions. These results are of further interest because these samples were not taken until 3.5 months after the fire and the fact that the effects of the fire are both visible (in the cloudiness of the water) and measurable (in the phosphorus levels) is indicative of the long-term environmental impacts of forest fires.

3.3 Observation of the Landscape

There was further observation performed at the locations the samples were taken from. *Picture 3* shows the location that Sample A was taken from. The water is very clear and there does not appear to be evidence of any serious erosion. However, the snow cover does make it difficult to determine the erosion levels. *Picture 4* was shot at the location Sample D was taken from. It is clear from the image that the water is much cloudier than that of the Upper Nambe. Another major difference is the apparent erosion: the banks of the river appear washed out and the the accumulation of broken branches and other debris indicate that flooding has occurred.

Picture 3: The upper Nambe River, the location where Sample A was taken.

Picture 4: The lower Nambe River, the location where Sample D was obtained.

4.0 Model

The model was constructed in Netlogo. Various elements of the code are described in the following.

4.1 Fire

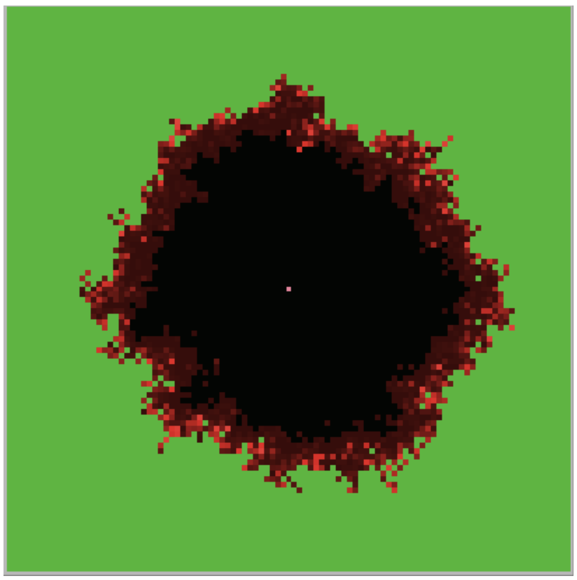
The fire is based on a cellular automata/empirical modeling method. A cellular automata model is characterized by a series of local interactions between cells, based on a global set of transition rules, on a latticed, 2 dimensional grid (Bodroži and Stipani). This model makes use of Moore's neighborhood (the eight neighbors that touch a 'cell' or a 'patch) and simulates the spread of fire from one patch to another every time step. The model is more empirical or statistical than physical. This means that the rules governing the spread of fire are based on acknowledged probable fire behavior and a simple energy balance rather than a theoretical model which would be based on mathematically established physical principles. A physical model would have the advantage of being able to process a larger range of input variables and might be considered to be more accurate. An empirical model, for our purposes, has the advantage of flexibility and a simpler design process that is based on qualitative research.

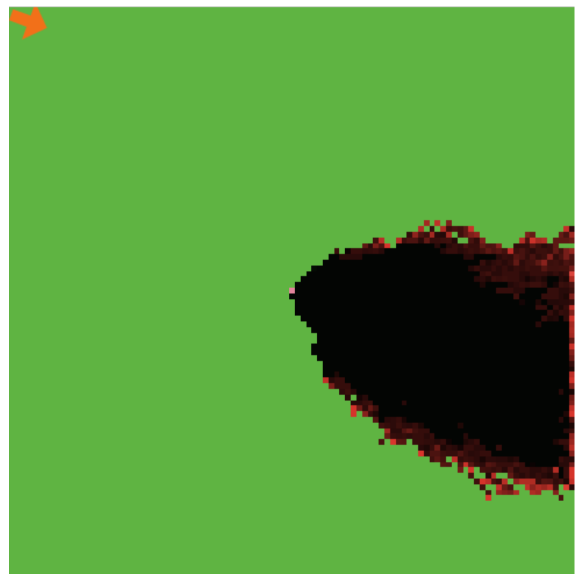
The fire spreading model is based on five primary variables; fuel, moisture, elevation, wind-speed and wind-direction. Every patch in the program has a value for fire, fuel, moisture and elevation. All of these values fall upon a sliding scale. Fuel is necessary for a fire value to exist in a patch, the higher the fuel value, the larger the fire value becomes, but at the beginning of each timestep the fuel is depleted based on the fire value. A value for moisture also is subtracted from the fire value, representing the ease with which dryer materials are burned. Moisture and fuel do not determine which patch the fire spreads to, that is done based on wind-direction, wind-speed and elevation. Global variables determines the wind-direction and wind-speed. At the beginning of each timestep, every patch with a fire value larger than zero examines its eight neighbors. It selects the one with lowest value for the number:

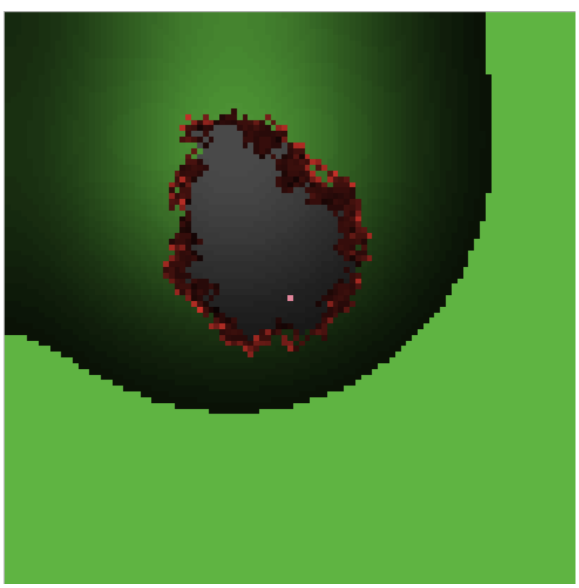
random((abs(pdirection - wind-direction) wind-speed) - elevation)*

Essentially, the patch most likely to be chosen is the one that has the heading (relative to the original patch) that is closest to that of the wind and that has the highest elevation. The selected patch ignites. The weight of the wind-direction in this equation is dictated by the value for wind-speed. This means that as the wind-speed increases, the fire is more likely to spread in the direction of the wind and when speed is very low, the fire is much more influenced by the elevation, burning uphill.

Here are examples of the fire model at its simplest, the pink square at (0,0) represents the starting point of the fire and the orange arrow points in the direction of the wind. Green patches still have fuel, black have neither fuel nor fire and red have some level of fire, brighter being higher. Moving clockwise, the images have: fuel only, wind and fuel, elevation and fuel.







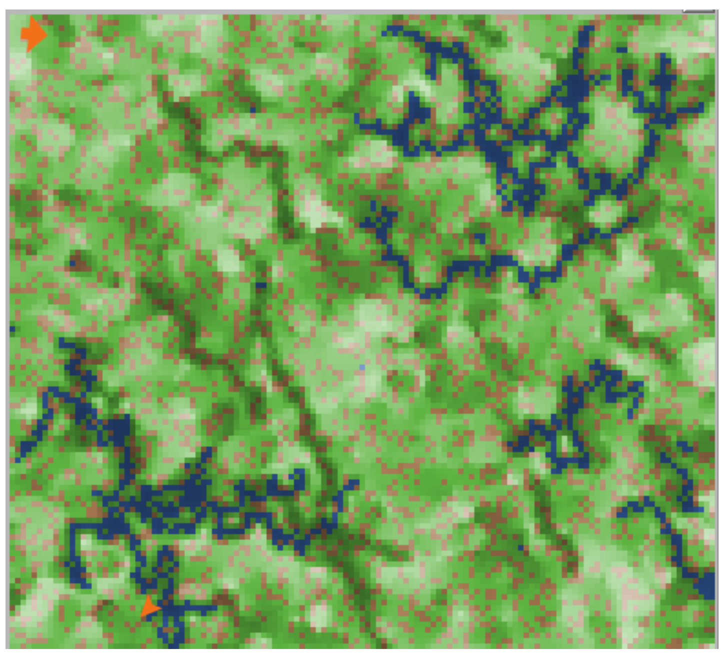
In addition to fire spread, the model also keeps track of the fire's intensity, based on the intensity equation:

I = Hwr

H, heat yield is calculated as the ratio of fuel to moisture in every patch. *w*, weight is determined by keeping track of the total number of patches burned. *r,* is found by dividing the total area burned by the time since the fire started.

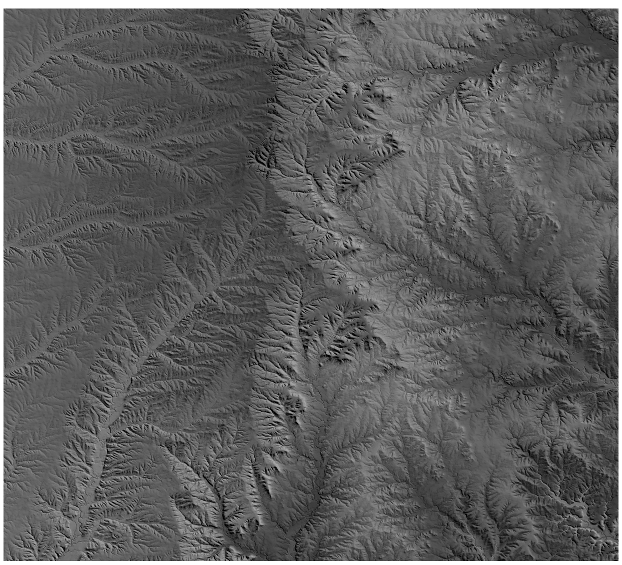
4.2 Landscape Generation and GIS

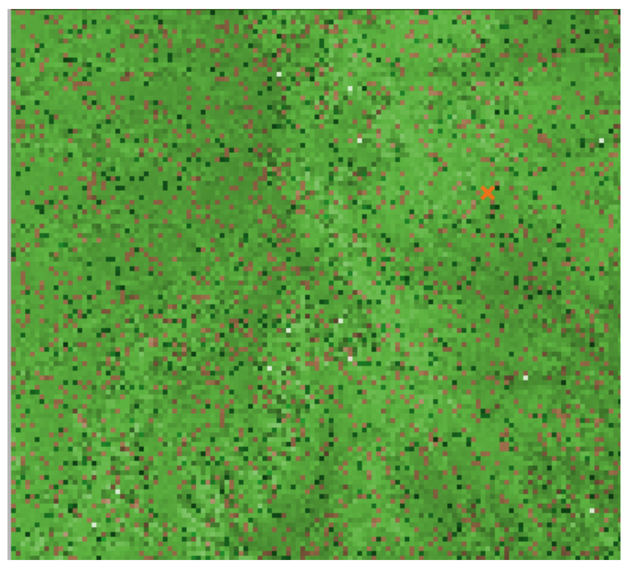
We used a randomized, procedural generation algorithm to create the test landscapes. The basic rules for the model are described here. First, all patches are set to either maximum or minimum elevation. Then, patch elevation is diffused evenly. Following this, 'origin patches' bring their neighbor's elevation level closer to their own height. Origin patches are picked randomly according to the 'elevation-roughness' variable; it ranges from 0% to 100% of the patches. In this model, 70% to 99% are used as default values for elevation-roughness. After this, grass is added according to biome type, patch fuel amount, and soil health. Lakes are then added to all patches below 1200 if altitude is set to lower or mountainous, or all patches below 5500 if upper are transformed into water. Trees are added according to tree density, if it is 95%, then 95% of dry patches are assigned a tree. Finally, rivers are made. Agents 'carve' rivers by making one or three patches in their path deeper and full of water, then smooth the surrounding dry land.



The biome types (Savanna, which is seen to the left, Temperate, Rainforest and Swamp) do not directly correspond to data for these land types. Instead, they represent relative moisture and fuel levels. For example, the Savanna land type is the driest of the four, followed by Temperate, Rainforest and Swamp. The Savanna land type also has the lowest fuel levels of the four, designed to represent a primarily grass based biome. The Rainforest and Temperate have high fuel levels, representing a high density of trees.

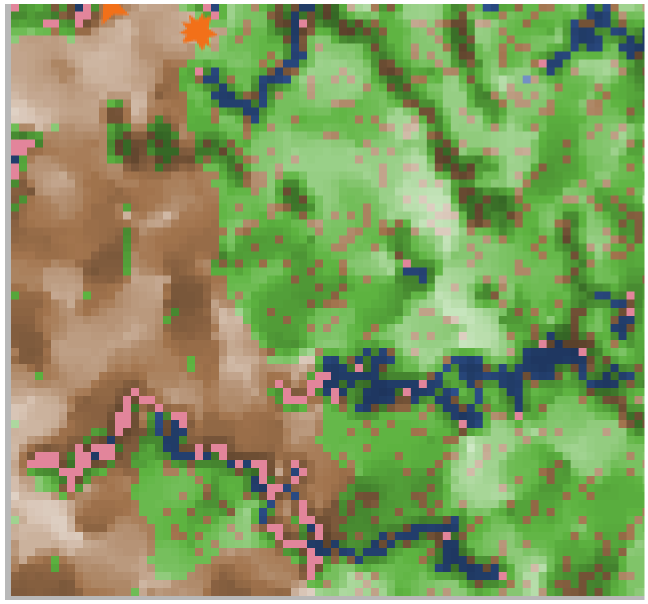
In the Netlogo model, GIS data can be used to create a landscape. This data must come in the form of a grayscale heightmap. A heightmap represents elevation data in an image file by assigning low elevation values to a certain range of colors, and high elevations to another range of colors. Our model uses dark grays to represent low altitudes, and light grays to represent high altitudes. Any grayscale image is acceptable input. After the elevation data is parsed by the patches, grass and trees are created. Patches below a user-defined elevation are turned into water. The images below are examples of a GIS heightmap and the corresponding Netlogo Model





4.3 Watershed Response

The watershed response in this model is represented by modeling the “debris levels” of the bodies of water in the given landscape. This is done by making any patch that no longer has fuel generate an agent. The agent travels as far downhill from its location as possible. If it happens to end up in a river, the debris-level of that patch is raised by one. The total pollution value for the model is calculated by summing the debris levels of all the river patches and dividing by the total number of river patches. This gives the value which for average debris-level per patch. In the model, the debris is represented by pink patches which appear after the fire



has ended. The aspect of the model is designed to replicate the effects of a rainstorm on a burned landscape by calculating how much much debris could be expected to be washed into a given body of water after a fire.

4.5 Scale

The scale of the dynamically generated landscape model's scale is roughly based on '1 patch = 1 square meter' scale. This means that the default grid (128 x 128 patches) is very close to being 4 acres in total. The timestep for measurement purposes is 1 tick = 1 minute. This is not an ideal timestep, but it is a reasonable approximation for our purposes. The timestep would be more important if the data being collected pertained to burn time, but the primary variables are area burned and debris levels, both unaffected by time. This scale does not remain the same for GIS landscapes

4.6 Firefighters

On of the goals of this project was to examine the ways fire damage might be mitigated with the protection of water resources in mind. One way fire damage is controlled is through firefighting. While not currently implemented in the main model, we developed another Netlogo model that is essentially a genetic algorithm designed to evolve the most successful firefighting techniques. The way this works is that the model begins with an initial population of agents with random values assigned for certain variables. The variables control things like the distance from the fire that an agent begins to 'dig' a fireline (this is accomplished by removing fuel from the patch), the length of the fireline and the direction the agent moves when it becomes close in proximity to the fire. These variables are designed to do two things; primarily to protect the agents from being burned by the fire and secondly to minimize the area burned by the fire. These priorities are reflected by the way further generations or agents are selected.

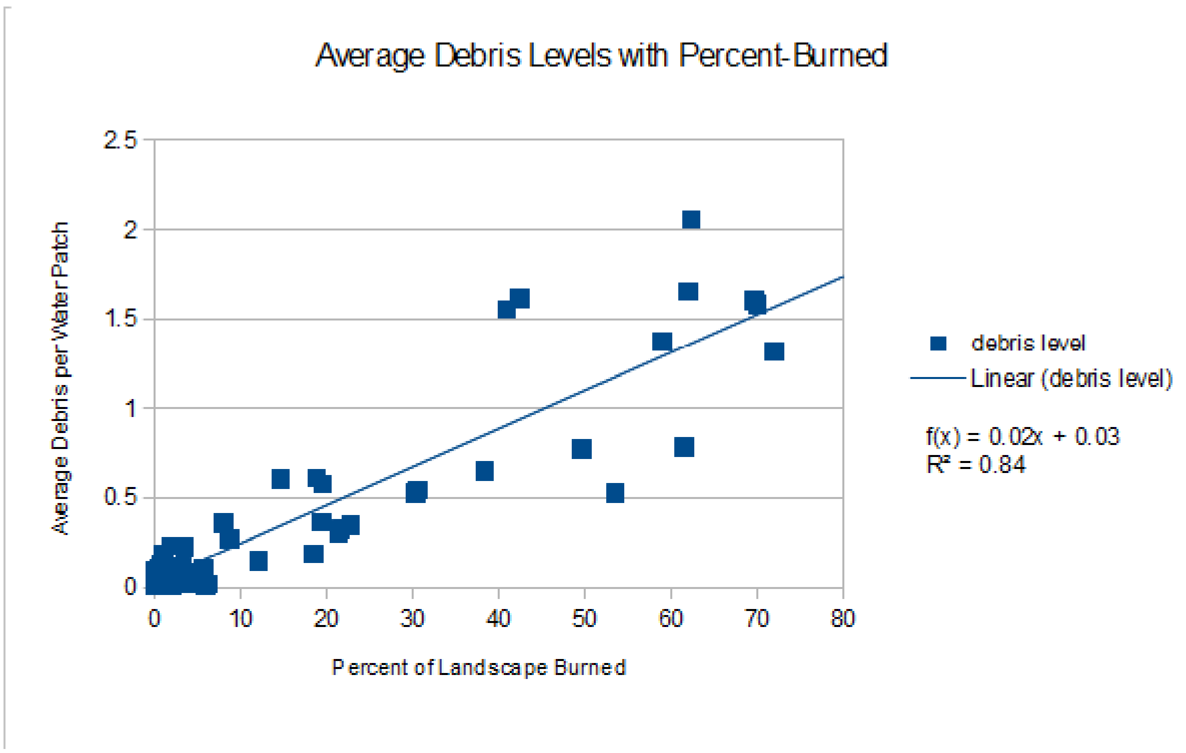
The process is as follows; when the entire fire has burned out, a new landscape is generated. The agents are then evaluated and ranked in 'fitness' based on how successful they were in avoiding the fire. The agents who have above average fitness then reproduce, passing their variable values down to their children and then dying. The children, ideally, represent the most successful parents and also have small amounts of random mutation, designed to promote diversity.

5.0 Data and Results

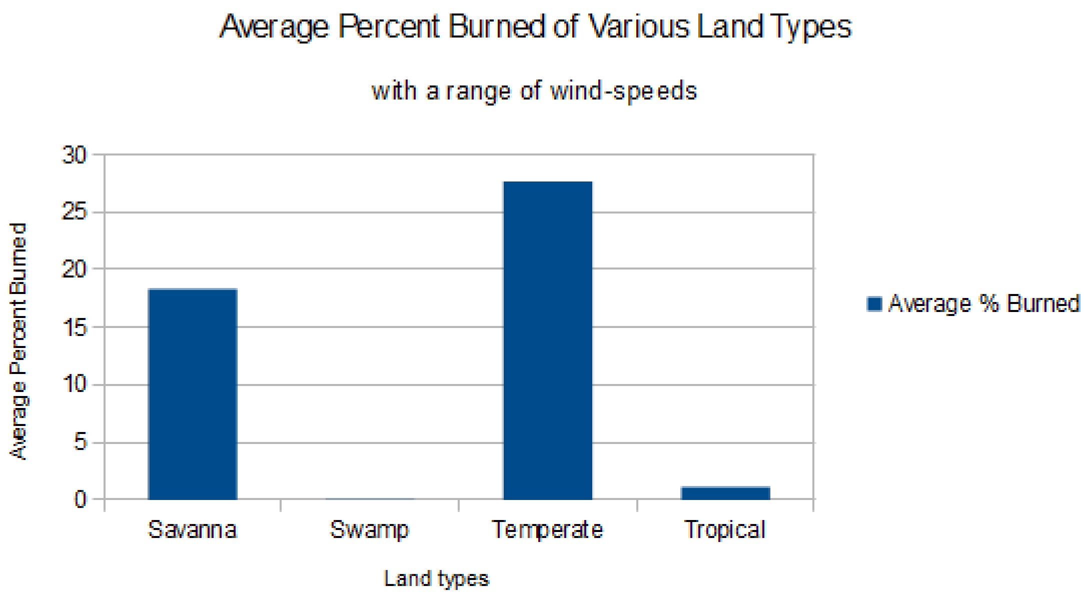
The primary measurements taken in these tests were the percent of the landscape burned and the average debris-level per patch. The graphs illustrate the correlation between the two as well as the impact of different variables on them. The experiments were conducted within Netlogo, using the Behaviorspace feature. The data processing was done in LibreOffice Calc.

5.1 Netlogo Experiments

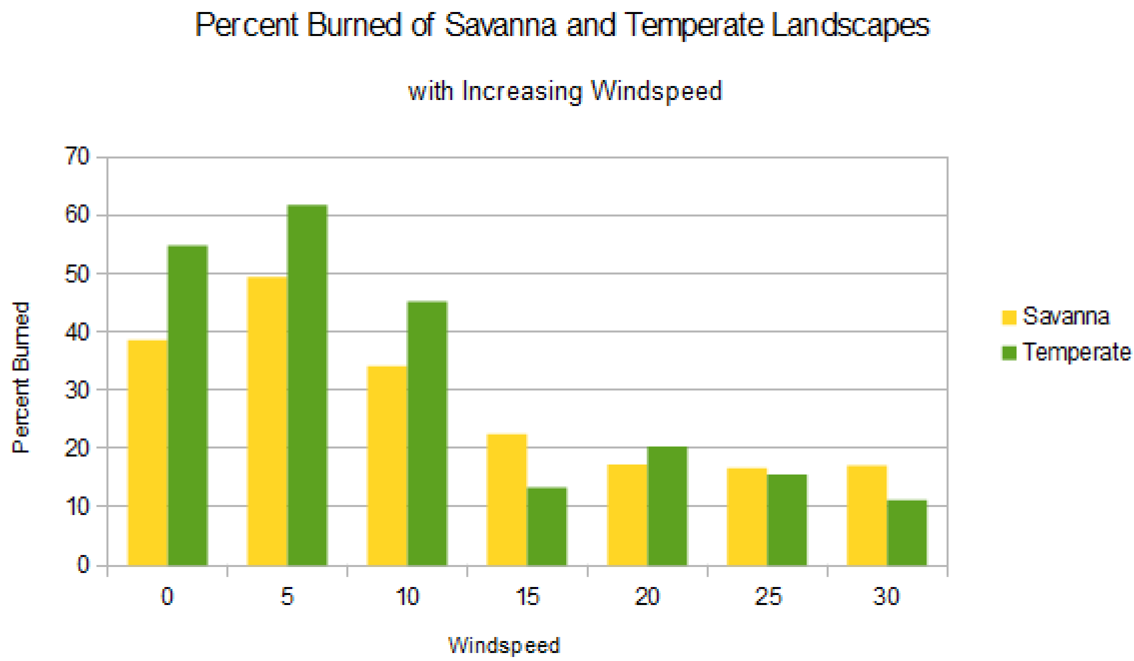
Correlation Between Area Burned and Average Debris Levels



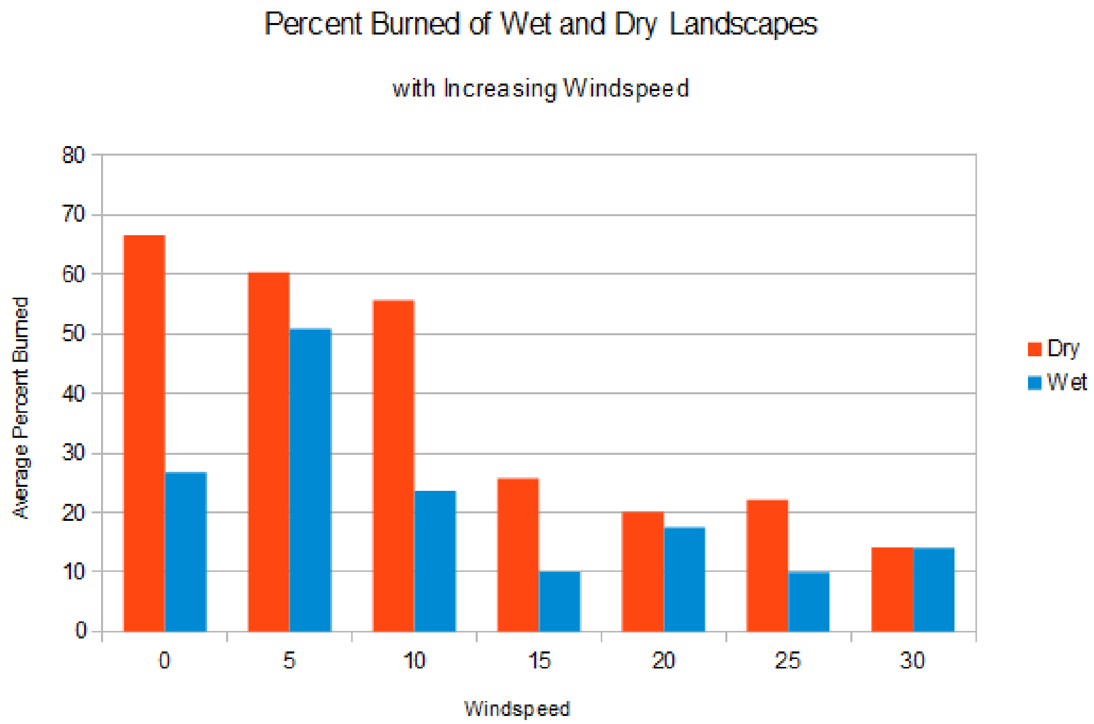
This graph has data taken from numerous trials of different land types and at different wind speeds (every land type, three repetitions of the windspeeds 0, 5, 10, 15, 20, 25 and 30). The reason that the majority of the data points are clustered near 0,0 is due to the fact the Swamp and Rainforest land types were included, and fire had very little effect on them. Overall, this graph demonstrates a positive linear correlation between debris-level and area burned. This is supported by the relatively high R^2 value of 0.84. The indications of these results are logical: the more land that is burned, the higher the average debris-levels will be in the rivers. The assumption of correlation is maintained throughout the rest of the analysis.



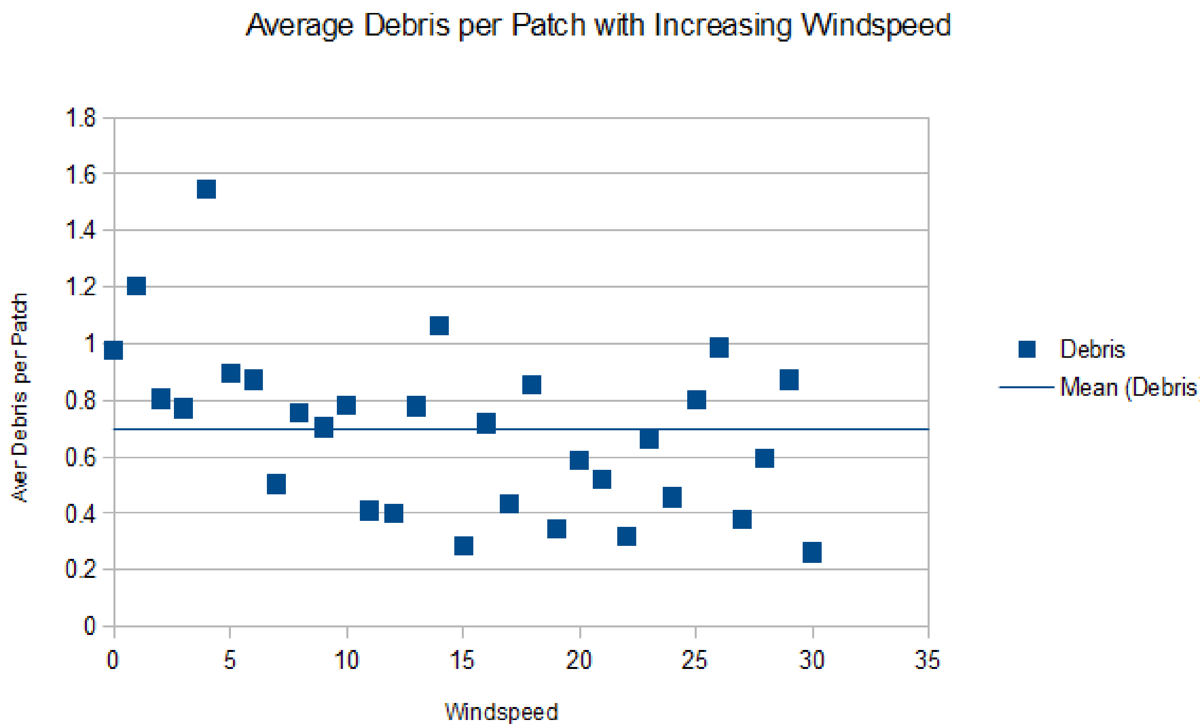
This graph is based on the same trials as the previous graph. It consists of the average percentage burned of the four landscape types, across a variety of windspeeds. It is clear from this figure that the impact of burns in the Swamp and Tropical landscapes are fairly negligible compared to Temperate and Savanna. Because of this, no more tests were performed on the Swamp and Tropical land types. Instead the tests focused on the land types which had large burn areas (and subsequently larger average debris-levels.)



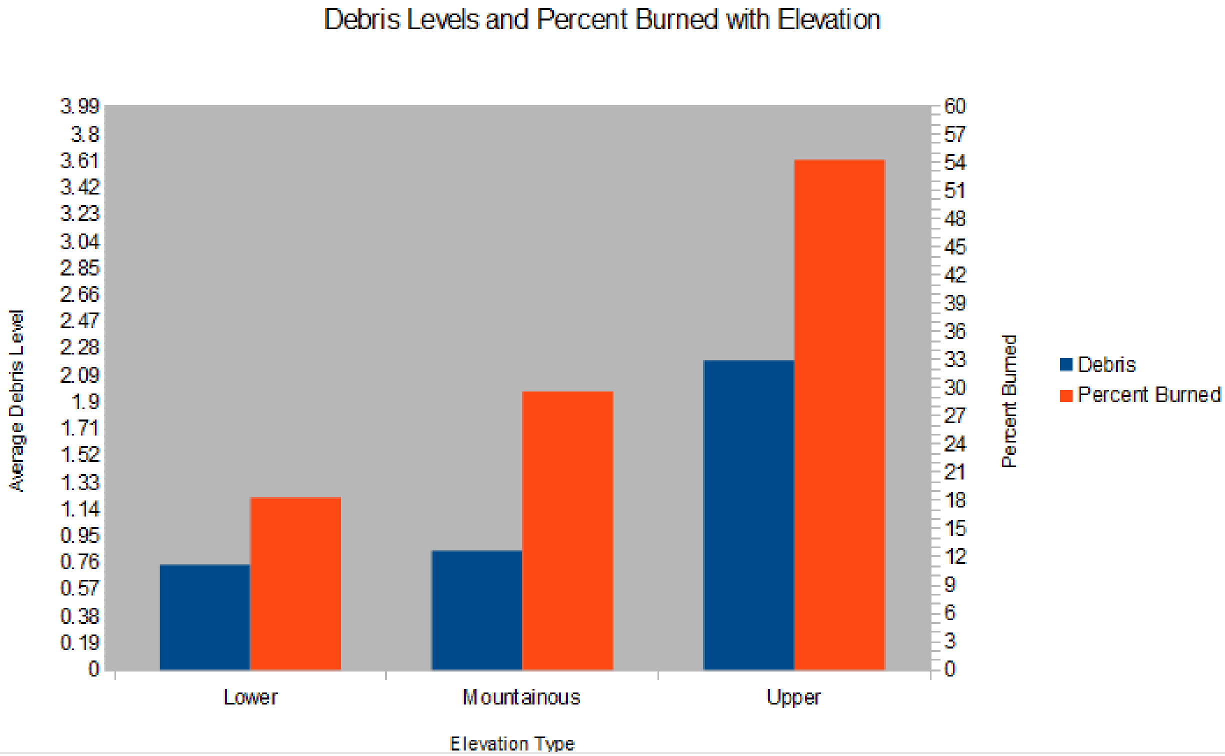
This graph is based on the same dataset as the previous two. It illustrates the differences in burn area between Savanna and Temperate land types. The downward trend of the area burned with increasing windspeed is immediately clear. This is a consistent trend throughout the experiments and will be discussed in detail at a later point. This figure also shows that when windspeeds are 10 or below, the area of Temperate forest burned is substantially higher than Savanna. However, Savanna passes Temperate at a windspeed of 15 and remains quite close from there on. This could be accounted for by the fact that the Temperate land type has more fuel, but is wetter than the Savanna and has more rivers. The higher fuel levels mean that the fires are more sustained and thus have more potential to speed. The increased larger number of rivers means that in the Temperate land type, higher windspeeds have a higher probability of putting out the fire along a river.



This graph shows the values for area burned for trials (from the same dataset as the previous graphs) separated by Wet and Dry. "Wet" landscapes are simply the landscape type with its average soil-moisture increased by 20% and the average number of rivers increased by 30%. The trend of decreasing area with increasing wind remains and it is also evident that, for the most part, dry landscapes have larger burn areas. This is what we would expect to see in a real-world situation. Fire will spread more quickly and persistently when it can more easily ignite fuel. When a fuel is very moist, or when fuel has been replaced by a body of the water, it makes sense that a fire would have trouble burning large areas. One notable exception to this trend are the values when the windspeed is 30. At this point there is no notable difference between Wet and Dry. This could be an anomaly, or it could speak to the unilateral impact of very high windspeeds.

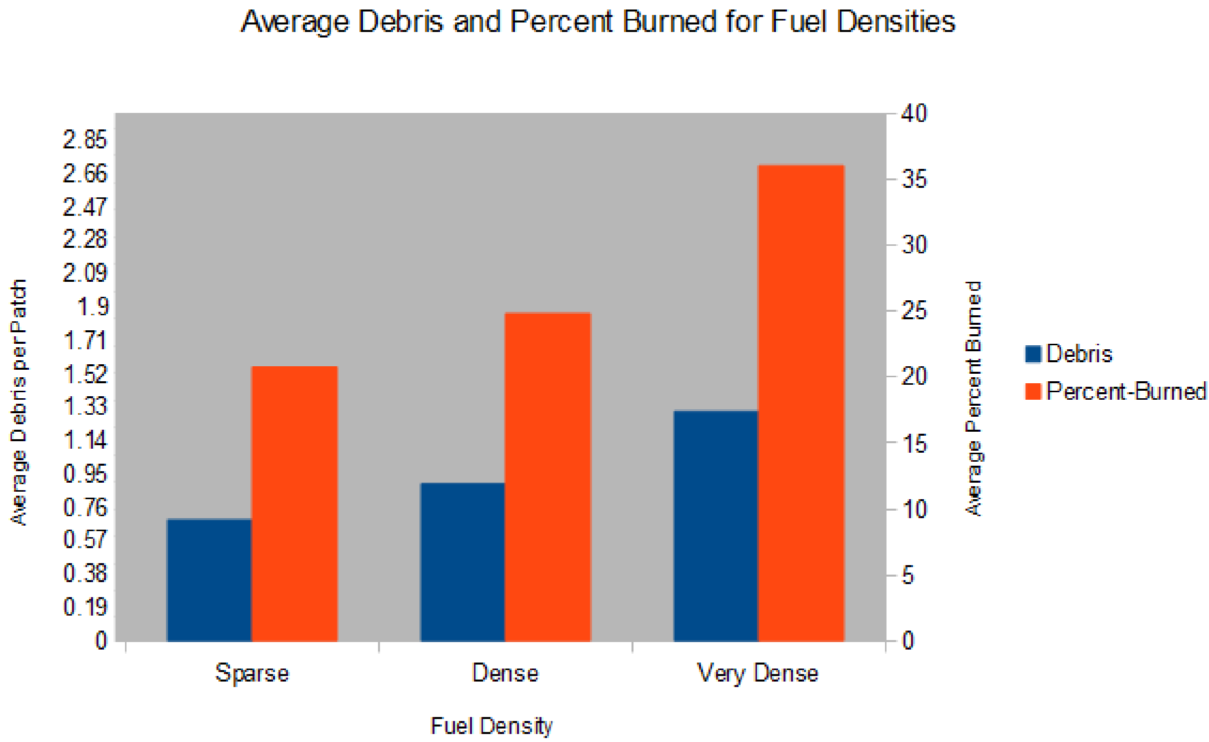


The data is this graph was obtained from a series of trials which tested Savanna and Temperate land types over windspeeds 0 to 30. The graph depicts the average values for debris levels per patch for each of the windspeeds. The trend, while not completely linear, does seem to trend towards lower debris levels with higher windspeeds (related, presumably, to the fact that previous graphs showed lower burned areas with higher windspeeds). The trend is evidenced by the fact that the majority of the points before 15 fall above the Mean and the majority of those after fall below. This trend is interesting and says a lot about the nature of our model. Basically, the higher windspeeds produced much more focused (though more powerful) fires. Very low windspeeds allow for more homogeneous fire spread, especially along the sides of watersheds as fire unbiased by wind has a tendency to burn uphill. This leads to larger debris concentrations for lower windspeeds.

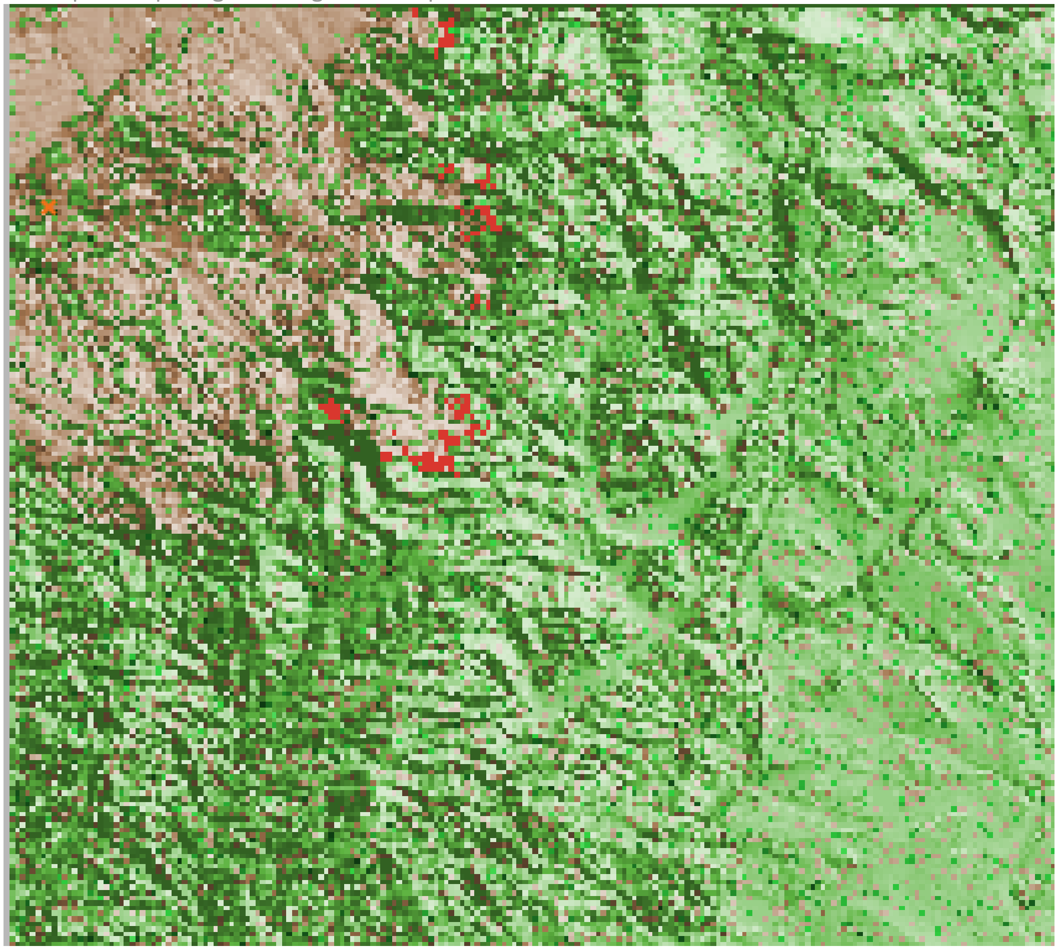


This graph is comprised of averaged data based on an experiment of repetitions of Temperate land types with different elevation categories at a constant windspeed of 15. The elevation profiles of Lower, Mountainous and Upper are assigned based both on the average elevations of the terrain types and on the variation between areas within the landscape. This means that Upper landscapes have higher elevation levels than Lower and they also have more variation, with lower corresponding to a flatter, prairie like landscape and Upper to high mountain ranges. Mountainous is an average of the two.

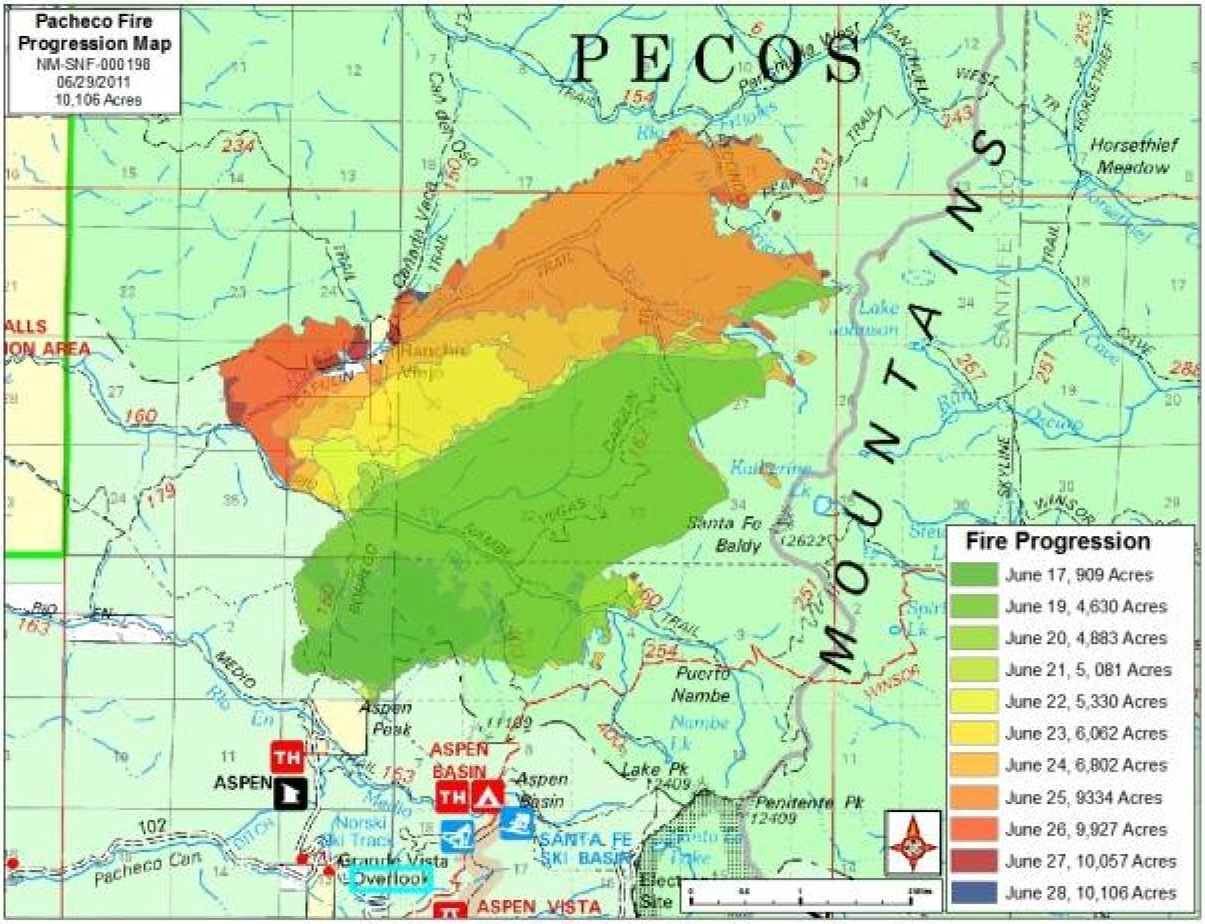
The results again show the correlation between area burned and debris levels. They also show a clear correlation between the elevation types and the area burned and a slightly less dramatic correlation between the elevation types and the debris levels. The Lower elevation type had less burn area and lower average debris. The next highest was mountainous, although the debris levels were close to that of Lower. The highest values were found in the Upper elevation type and they were substantially higher than the others.



This graph consists of data collected from numerous repetition of Temperate land type at a windspeed of 15 over various 'Tree Density' levels. The trend again shows the correlation between debris level and area burned. Additionally, it is clear that there is a relationship between the tree density and the debris levels and area burned. The varying density levels essentially refer to the evenness with which trees are spread across the landscape. The value assigned to Tree Density reflects the probability of a given patch receiving a full load associated with a tree (much larger than the value for grass). These results make sense because it is expected that a fire with access to more fuel would burn more area, and as previously demonstrated, more burned area means that there will be high debris levels.



This image is the Netlogo processed elevation data for the Santa Fe National Forest, focusing on the area where the Pacheco Canyon fire burned. The burned region represents a test exploring the correlation of our model to an actual fire. The starting point (signified by an orange 'x') is close to the starting point of the fire. The progression map from the actual fire is shown below. The characteristics of the Pacheco fire were that it started in the Nambe river watershed, initially spread east, uphill towards Santa Fe Baldy and then North, uphill along the side of the Nambe drainage. Our model by no means produced a perfect replication od the Pacheco fire. The fire in our model grew larger and did not stay within exactly the same drainages as the real on. However, considering that we did not account for wind conditions and the fuel approximation was very rough, our model demonstrated striking similarities. The fire was ignited and began climbing the sides of the watershed, at the same time burning quickly uphill towards Santa Fe Baldy. The fire was stopped at points of sharp downhill slope and burned quickly uphill, slowing as it approached the divide. This model did not include bodies of water, but it is evident based on where the fire burned that large amounts of debris would be expected in the Nambe and Capulin rivers, the rivers our water samples were taken from.



6.0 Conclusions

The results of these experiments point to several important trends, which both comment upon the validity and usefulness of the model and provide a new perspective on the subject.

6.1 Improvements

As an empirical model attempting to represent a complex environment, there are naturally many simplifications. We attempted to isolate variables important to our question, the primary variables explored were: wind, slope, fuel and moisture. Improvement along the lines of these variables include the following. The use of GIS data for fuel and moisture profiles could help standard the fuel assumptions made in the model and help bring them into the real world. At this stage, the model has a direct correspondence to elevations, but fuel and moisture are estimated and standardized only relative to each other. Also, method of programming in or otherwise accounting for various weather patterns could help with both wind variables and moisture. Additionally, if we wish to establish a more predictive model, it will be necessary to standardize the scale and timestep.

6.2 In Summary

Despite the simplifications of of this model, we were able to gather interesting and useful information.

For example, some of the most interesting results have to do with the impact that high winds have on forest fires and the areas that are burned. Based on trials and observations from our model, we came to the conclusion that higher wind speeds often result in a smaller area burned, due to focused fire, heavily influenced by the wind. However, the high windspeeds did create fires that were a lot more persistent, for example they could pass through very low fuel areas without going out, where fires with low windspeeds would be stopped. This points to the fact that a constant windspeed could be a very useful factor in predicting the the direction and speed of the fire. Wind has the power to dramatically changing the direction of the fire. In some cases, the high winds forced the fire against natural fire lines, such as rivers or canyons and helped to extinguish the fire relatively quickly. Although this would be very negative if, for example, the fire was being forced towards a town. In our model, the wind direction remained fairly constant, but in a setting where the this was not the case, this could cause to a highly unpredictable and dangerous fire.

Another important conclusion of this project is the impact that various elevation profiles can have on both fire spread and post fire debris. The experiments demonstrated that fires burning in mountainous regions had great potential to affect water resources. This is something that has been observed in landscape studies in New Mexico (Veenhuis). The results pointing to this in our model were partially due to the fact that fires do best when they are burning up steeper slopes, and therefore are likely to burn more area. In the real world the impact of this fires on water resources in areas of uniform elevation is magnified due to increased erosion potential of steeper slopes (which our model did not account for).

The experiments conducted within the GIS terrains, particularly where the Pacheco Canyon fire burned, showed that would model has some amount of value as predictive tool, at least as far as behavior with respect to slopes and general fuel profiles.

Currently the firefighter portion of the project has not been completed. There are some results which have illustrated the value of fire lines as a firefighting technique. More than anything, the current firefighter program illustrates the principle that single, unconnected, uninformed firefighters are highly disadvantaged. It has demonstrated the importance not only of global communication between the firefighters, but of a global appreciation of the behavior of the entire fire.

The results from these experiments are potentially important to firefighters as well as humans who live near or depend on water resources that pass through fire zones. This type of information allows for predictions about the movement and severity of forest fires as well as the expected post-fire watershed response.

7.0 Appendix

Acknowledgments

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