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Wildfire Simulation Using Agent Based Modeling: Expanding Controlled Burn Season

Morgan C. Kromer
The College of Wooster, mkromer22@wooster.edu

Wildfire Simulation Using Agent Based Modeling: Expanding Controlled Burn Seasons

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Morgan Kromer
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Dr. Long (Mathematics)

THE COLLEGE OF WOOSTER

Abstract

The United States is home to many different and unique forests. Prior to the 21^{st} century, the United States Forests Service assumed that the best way to protect these forests was to put all efforts to keeping them alive. An enemy to these efforts were wildfires, thus the US adopted a complete fire suppression approach.

At the turn of the century, the US realized that wildfires are a necessary part of a forest ecosystem, as they help return nutrients to the soil and reduce ground fuels. However, after suppressing all fires for over 100 years, the forests evolved into a weakened state, making them prone to large scale, destructive wildfires. Paired with a changing climate, fires are now costing billions of dollars each year, with no expectation of changing.

One way to help reduce the threat wildfires pose to surrounding communities is to participate in a series of prescribed burns. These burns allow the forests to participate in their natural ecological life cycle, while making sure that personnel are on hand to contain the fire before it spreads out of control. The issue is the time of year in which the environmental conditions are deemed safe for controlled burns is decreasing, while the time of year in which uncontrollable wildfires are occurring is increasing.

To help expand the amount of time each year in which controlled burning can happen, I used agent based modeling to help examine the effect extreme conditions have on wildfires. By better understanding how the conditions are effecting the size, spread, intensity, and speed of a fire, it is easier to predict how an actual fire

will respond to more extreme conditions. Those findings can help to increase the amount of time a community can do controlled burning, as it can help communities know how the controlled burns could possibly spread out of control.

This work is dedicated to my home community of Eagle County, located in Western Colorado, which has a penchant for catching on fire every summer

Acknowledgments

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CHAPTER 1

Introduction

I grew up in the mountains of Western Colorado, in the small town of Eagle. I remember one summer I finished my karate class in middle school, walked outside on a stormy day, and watched a lightning strike fire start north of my house. At the time, that was a rare occurrence. Everyone in the neighborhood had to quickly prepare for the moment our pre-evacuation turned into an evacuation. Up until this point, the threat of a wildfire close to our house wasn't something most members of my community had dealt with. I got a ride home before they closed the road leading to my house so that I could pack my evacuation bags. Things I included where photographs, childhood toys, and art project I made when I was young. Following that, my family went around the house and took pictures of everything in case the fire spread close enough to potentially damage our home. There was a sense of fear in my house that I had not experienced before. Once everything was packed, we were able to appreciate the beauty of the fire, knowing that there was nothing more we could do at that point to prepare. Fortunately, I live near an army base that had helicopters in the air quickly and they were able to subdue the fire, so we never had to actually evacuate, and those evacuation bags were unpacked at the end of the summer without ever having left the house.

Now, that rare-occurrence lightning fire I witnessed almost a decade ago is a common occurrence. During the summer of 2021, in one lightning storm Eagle County had 9 such small fires break out around the county. It was on a day that the fire department was prepared to deal with the fires, so none of them grew to be a noteworthy size. Natural fires, such as those caused by lightning strikes, are growing in occurrence and impact across the United States. However, there are other causes of fires than just natural ones. Most fires in the country are human-caused fires. The congressional research service found that from 2016 to 2020, over 85% of the wildfires in the US were man made. However, the scope of the damage of the fire has minimal relation to the cause. From the same research article, lightning fires were found to burn more acreage on average than fires form other sources. Lighting fires accounting for the majority of burned acreage during the 2016-2020 period, despite only accounting for a small portion of the total number of fires [28]. Regardless of the origination of a fire or the reason for it's existence, any uncontrolled fire is considered a natural disaster by the Environmental Protection Agency [58]. One of the reasons is due to the uncontrollable nature of fires, which has nothing to do with the type of ignition that started the fire or the location. Regardless, uncontrolled fires can be, and often are, destructive natural disasters, and are portrayed in media as damaging to our forest, destructive to our ecosystems, costly, and dangerous. For a while, they were perceived as a threat to our society, environment, and resources. While their impact on human lives is often significantly less than other natural disasters, our ability to alter their natural course has led to very aggressive fire management.

Since the start of the 1900's, the United States adopted a fires suppression management style, in which all fires were suppressed as quickly as possible[50]. The idea was to protect the lumber economy. Increased fire activity resulted in decreased quality and quantity of lumber. Another view in support of fire suppression techniques was the thought that fires destroyed natural habitat and resources that animals needed. Which, given the severity of wildfires today, is partially true. The significant loss of landscape caused by wildfires does pose a threat to local animal species and even plants that inhabit the areas that have been effected [17]. This is partially due to the intensity of destruction modern day wildfires create. However, for centuries, American forests relied on wildfires to maintain overall forest health. Wildfires help reduce dead material buildup on the forest floor, release nutrients back into the soil, and strengthen the forest ability to fight off pest infestation, such as the current pine beetle infestation in the Rocky Mountains [3]. The complete suppression effort used in the 1900's has left our forests weaker, and thus more prone to worse fires. In addition to the active methods of fire suppression weakening our forests, the changing climate is also posing a greater risk of more extreme fires. There is minimal debate that we are facing a climate that is different from the last century, the effects of which are longer, drier summers and increased temperatures. The changes create greater conditions for fires to both begin burning, and better conditions for fires to continue burning once ignited.

With an increase in the danger of unplanned forest fires comes larger threats to communities, and a high price tag per fire. 2020 alone cost over 2 billion dollars in fire suppression efforts, and 2021 came with a price tag of $4.4 billion [29]. There is no clear solution to reduce these costs, as there is no way to eliminate the fires from existing. However, there are steps that can be taken to reduce the costs of fires. The goal is to reduce the overall severity of fires. Methods to do this are more proactive and controlled burning, which allows forests to naturally help regulate themselves in safer burning conditions. In addition, raising awareness of what conditions cause more extreme fires can help reduce the number of man made fires each year, by better demonstrating the catastrophic effect that can happen.

In my IS project, I use agent based modeling in Net Logo to study the effect different conditions have on wildfire spread and burning characteristics. Agent Based modeling is a type of modeling that relies on the small pieces to make the simulation, rather than a determined differential equation commonly seen in other types of modeling. The goal of this project is to determine what factors make fires burn in an unpredictable and unsafe manner. I will be primarily looking at environmental factors that humanity has little effect over, so instead the conclusions will be used to address times of year that burns should happen. Ultimately, the information learned in this project could be used to expand the amount of time my home county could use controlled burning to help the health of our forests and reduce the impact wildfires may have.

CHAPTER 2

Management of Forests

The first step in understanding why wildfires today are more costly and destructive than 10 years ago is to look at how forest management practices have lead to a weakened forest. In addition, it is necessary to look at what other environmental factors are contributing to more extreme fires, and how they are likely to only get worse.

The United States consist of many different landscapes and ecological classifications. About one third of the land in the US is classified as forests, many are private. In addition, a large portion of the US forests are used for timber production, across both private and public lands [47]. Much of the public land was designated as National Forest Reservations, later renamed to just National Forests. The forests contain many different natural resources, create beautiful scenery, and provide good locations for nature education. The question of how to manage and maintain these forests has existed as long as their designation as National Forest [20].

For most of the Earth's history, fires have been able to start, spread, and burn at the rate and pace of the natural forest, given the fuel type and environmental conditions at the time. Those fires served to help maintain the overall health our forests. Prior to colonization and western expansion, Native Americans helped the forests stay healthy by practicing slash and burn methods [34]. Slash and burn method forest management involves lighting fires to help clear underbrush, thin out weakening vegetation, and provide nutrients into the soil from the ash. In addition, there is evidence that Native American tribes would use fires to help drive animal herds. They would light fires in the forests to push animal herds to the prairies, or even light fires to help clear out the prairies to make them more welcoming to the herds [43]. Once Native Americans were done using the land, they left it to grow back into a healthy section of forest or other open land. When colonists such as John Muir later arrived in areas they had historically housed large tribes of Native Americans, they found the areas to be “untouched” by human hands. The reality was generations of Native American tribes respectfully shaping the land to be the most advantageous to the tribes without removing the natural beauty of the landscape [43]. The relationship tribes had with using fire helped in two ways. The first was it ensured that the land stayed rich in nutrients, and thus fertile for future sprouts to grow. The second was it helped the forest maintain its natural processes of nutrient recycling. In addition to the intentional slash and burn methods for the land they were cultivating, Native Americans also let natural fires burn their course. While that may have been a more resource driven decision rather than intentional forest management decision, it still resulted in healthier forests overall.

In addition to the evidence of human interaction, it has been found that prior to any human presence, lightning provided the ignition for many natural fires to take course through the forest lands. The oldest trees in the United States are thought to be well over 3000 years old [12] and likely have endured many fires to help them stay healthy. There has been specific research on the effect of fires on giant sequoia trees, and it is now known that the fires play a vital roll in maintaining the tree health. Many of the giant sequoias have significant burn scarring along their trunks. Similar to slash and burn methods ability to maintain vegetation, natural fires clear thick underbrush, burned dead trees and provide nutrients for young trees and foliage to take root and grow healthy and strong.

2.1 Historic US Forest Management

To help maintain the 764 million acres of forest lands [32], the United States Government started the Unites States Forest Service. The original purpose, as is quoted on their website, states "Congress established the Forest Service in 1905 to provide quality water and timber for the nation's benefit" [48]. It was started at a time in which expansion, finding the American Dream, and increasing personal wealth was a large goal of the United States, and timber was required to support that dream. The focus on maintaining biodiversity and ecological or environmental health was not a primary objective when deciding what methods of management should be used. Shortly after the Forest Service was founded, a raging fire burned more than 3 million acres in two days the north west of the United States, killing over 80 people [30]. This fire sparked fear in the United States people, and was used as evidence to the potential damage a fire can have. In addition to seeing forests as little more than timber resources, and only being exposed to the more negative consequences of forest, the understanding of how fires help to maintain and sustain the forest was far less than what we know today. Through that, the connotation of forest fire was extremely negative, only really seen as a threat.

By establishing timber as an objective and spurred by the destruction of the fire, the United States tailored management methods to those that they deemed best at protecting the precious resource. From that, the United States Forest Service adopted a complete suppression and avoidance policy, where all fires were to be suppressed as quickly as possible. To accomplish that, fire fighting programs grew in funding and size, the narrative was to eliminate all potential fires, and training and resources were dedicated to fire suppression tactics. The forest service explicitly educated against controlled burning of land, despite many ranchers, timber men and other experts arguing for its beneficial use [20]. Ultimately, the narrative painted fires as being unnecessary and harmful as they destroyed standing timber, arguing any and all fires needed to be eradicated completely.

Following the great depression and a couple years of increased wildfire activity, the government saw a need for younger men to be employed and a need for more people in the National Forests to help with fire response. The result was the creation of the Civilian Conservation Corpse which helped employ more than 300,000 men across the Western United States to help plant more trees in forests, build forest lines and ultimately help with fire suppression should a fire arise [6]. It only existed for a short period of time following the great depression, but played a vital role in shaping the nation's narrative on the importance of timber preservation in the National Forests, and the role of fire suppression as well.

In addition to just the forest service's role in forest management, a burden of management was placed on the general population. During World War II, many firefighters were deployed overseas, reducing the resources available within the states. From that, a campaign to improve people's knowledge about their ability to create wildfires grew. The idea was that the general population could reduce the total number of wildfires simply by being more aware and more careful of their actions that could lead to a fire. As stated in section 1, a majority of fires started are started due to human causes. In 1944, Smokey Bear became a public figurehead, spearheading a campaign that is still present today. At the time, the slogan he promoted was "Smokey Says – Care Will Prevent 9 out of 10 Forest Fires," which changed only a few years later to be "Remember - only You can prevent forest fires" [8]. The goal of the campaign was to remind the general population that they had the ability to help reduce forest fires by being more conscious with their actions.

Through the numerous campaigns and total suppression policies, the United States did do a good job at preserving the quantity of timber in the forest. According to the Food and Agriculture Organization of the United Nations, the US has succeeded in reducing the amount of land burned due to wild fires every year since the start of data collection. Comparing amount of land burned in the early 1900's to that burned at the end of the 1900's, the total area declined by over 90% [18]. That decline helped prevent hectares of land and precious timber from burning, which would have burned the much needed timber supply. In one patch of forest in California, records show that in the early 1920's only 19 trees could be found on an acre that now has 260 trees per acre [30]. For many years the policies the United States were using, which lead to a boom in forest density, were very sustainable. Beginning in 1920 up through the end of the century, the United States continued to produce more new wood in forests than they were consuming, and saw an increase in biodiversity within the forests. The impact of the fire suppression method seamed to be working out well, providing better access to resources and protecting the forests. As our knowledge of the benefits of the forests increased, the forest service shifted their focus to be more than just timber and water resource preservation. Their goals grew to included sustaining wildlife and biodiversity, and provide natural recreation locations.

However, around the mid century increasing research into the benefit of fires in forests increased. Slowly the stance on total suppression lessened to allow for some natural caused fires to be contained rather than suppressed, which improved forest health. With a weaker stance on fire suppression effort, paired with particularly fire favorable conditions coincidentally happening at the same time, a couple fires spread at a rate which was deemed unforeseen, yet preventable, if the United States had been following the strict fire structures put in place before. Those fires, coupled with the national perspective on the dangers of fires, only amplified the national voice to suppress fire entirely. It wasn't until the century turned that the narrative of the relationship between fire and forests really changed. With it came a change in perspective on the health of the forests as well. Instead of the forest being rich with lumber, the narrative was switched to forests being choked with lumber. Instead of higher rates of biodiversity and small ecological niches, animals were struggling with greater competition for less resources. Rather than thriving, forests were beginning to suffocate. It was realized that fires played a vital role in protecting the forests, the precious timber, and the animals that dwelt within. Rather than protecting the forests, the fire suppression methods used during the 1900's made the forests ripe for devastating fires, natural pest outbreaks, and weaker trees.

2.2 Current Forest Management

The expansion of knowledge and understanding about letting the land burn to maintain the forest has changed the narrative of forest management. Given all the evidence for the benefits of burning, the United States slowly shifted to allowing more controlled burning and free burning. The United States Forest Service issued a memorandum in 1995 which outlined the goals and guiding principles of the Forest Service moving into the new century. In the memorandum, they included the guiding principle "The role of wildland fire as an essential ecological process and natural change agent will be incorporated into the planning process," the second principle on their list only after safety of firefighters and the public [25]. In addition to merely a policy change, the United States also began focusing on the effects the prolonged fire suppression efforts had on the environment. Studies on current fires found that the extended periods of time without fires were negatively impacting the severity of new fires. Studying the Buffalo Creek Fire near Denver in 1996 found that the current state of the forest allowed for the fire to burn hotter and larger, which played a roll in causing a devastating effect on the soil [15]. The result was a burn scar which led to flooding in the following year. A burn scar is the area of land left behind after a fire. It typically has little to no vegetation, drier, darker soil, and typically absorbs little to no moisture. Due to the change in soil type, it is more likely to result in flooding, erosion, or other potential dangerous environments with less rain. In addition, the drier soil increases the strength of lightning storms, which could cause more fires in the future [14]. To mirror the focus from preventing all burns to reducing wildfire burns, in 2001 the Smokey Bear slogan changed to be "Only you can prevent wildfires" rather than the earlier wording of Forest Fires. For decades he had served as the figure head proclaiming that humans had the power to prevent most fires, and was widely recognized as a symbol of fire suppression and avoidance. The shift in logo was aiming to shift the public to a better understanding of the importance of planned fire in forest management [8]. Following the new narrative, the US saw a push to welcome certain types of burns to maintain the forest health. Florida was one of the first states to lead a management style that actively shifted efforts toward increased controlled burns. It passed the first law encouraging the use of controlled burns and prescribed burns in 1990, however private land owners had been using controlled burns for the past century already to maintain the health of the landscape on their property [34]. Since then, the popularity of the burns has significantly increased, mirroring the sentiment rancher had prior to the United States push to complete fire elimination. Currently, 70% of the prescribed burns in the nation happen in the southeast [50]. The reasoning is in part environmental and in part social. By creating some of the first laws explicitly supporting and encouraging prescribed burning, the custom of the area better supports burning without as much negative stigma from the community. In addition, the wetter seasons found in the south create safer conditions to do controlled burning before and after harvesting seasons.

In the west, the health of the forests paired with the change in climate has led to more extreme conditions which lead to more unpredictable fires. From those conditions came an increase in the duration and intensity of fire season, limiting the time available for controlled burns. According the the Forest Service in 2015, "Climate change has led to fire seasons that are now on average 78 days longer than in 1970" [49]. In parts of Colorado and the Western United States prone to less precipitation, severe droughts are extending the season even further. Colorado Governor Jared Polis even stated there is no longer a fire season, but instead it is a "year round phenomena" [38]. During much of the fire season, counties, states, and the US National Forest Service place orders, called red flag warnings, to cease any and all controlled or prescribed burning until the environmental conditions are at a level that is less likely for the prescribed burn to become a wildfire. Much of the summer months experience conditions that are too hot, too dry, and too windy to allow controlled burning in parts of Western Colorado that desperately need it.

Despite the conditions in the summer being non-optimal for controlled burns, the United States, specifically Western Colorado and Western United States, have adopted a passive containment approach on wildfires so long as the conditions for a passive approach are favorable [53]. Once a fire is not threatening any structures and away from the urban-wildlife interface, many fire management teams are scaling back suppression and containment efforts to allow the fires to burn. There is still some risk with this method, as was seen in the Tamarack Fire in California in 2021. It was started by a lightning strike, and was allowed to burn because it was deemed safely away from the urban-wildlife interface, and not posing a high threat. However, a rapid change in environmental conditions cause the fire to spread very quickly, and it grew to consume multiple homes and almost 69,000 acres [54]. Much of Colorado, Nevada, Utah, New Mexico, Wyoming and Eastern California provide open space with sparse population clusters that allow for this large scale burning. Two large scale fires in or near Eagle County have been left to burn out naturally once no structures were at risk. Both fires were able to burn decent portions of forest service land and leave less than 10 structures combined affected despite the long burning time. Allowing these prescribed burns reduces the total cost of fire suppression, as natural changes in weather account for a decent portion of the fire suppression. In addition, allowing the fires to burn more had an added benefit of reducing the amount of forest that is considered higher risk for burning in the future years, as more forest is allowed to burn during the controlled burn.

On the opposite end of the weather spectrum from the hot dry summer, is when the weather is colder with more moisture in the winter. During this time, the amount of precipitation and snowfall increases, covering the thick underbrush, making most controlled and prescribed burns less effective compared to parts of the year with less snow. To start a controlled burn during these months would prove only minimally effective at successfully reducing the fuel found on forest floors that contribute to the risk of massive fires. A research project from Portugal that studied the maritime pine tree found that once the moisture of a plant is above 35%, the likelihood of burning is lower than 50%, and prescribed burns can lead to a burnout rather than a successful burn [19]. As the temperature decreases, that moisture threshold also decreases, meaning less moisture would be needed to reduce the likelihood of burning lower than the 50% threshold. While the maritime pine tree is uncommon to the United States, it is related to the Pinyon Pine tree commonly found in the Western United States. While it most likely has a different fire resistance than the maritime pine, the trend found by Ferenandes can be carried over. Most of the western forest land is at an impasse where the amount of prescribed burning that would need to be done to keep our forests healthy and our fires safer cannot be done in the amount of time and resources available to allow prescribed burns.

Two larger scale fires have happened in or near my home community within the past 5 years, the Grizzly Creek and the Lake Christine Fire. They transitioned to prescribed burns and were declared 100% contained only when the winter snow hit. Even the following summers, hot spots still remained and the fire was not declared completely out until a the following year's winter. One drawback with the burn it out approach is the lack of containment at that border of the fire. The decision to transition a fire management from a wild fire suppression approach to a prescribed burn approach comes only after a significant enough distance from the Wildlife - Urban Interface that the risk to infrastructure is almost nonexistent. By creating more accurate, visual models to help predict the spread of fire given certain circumstances, allowing wildfires to transition to prescribed natural fires at an early stage can help reduce the costs of the fire suppression and increase the amount of forests that can benefit from the fire.

A different alternative to forest management than fires is an effort to reduce the amount of vegetation present in the forest through various means. Such means include manually removing fallen timber, cutting down older drier trees that are likely to have little defense against a fire, and thinning out overgrown sections of the forest. The flaw in these other methods of management are the amount of manual resources required and the difficulty in accessing certain terrains. While these are more effective methods of managing wildlife urban interface areas than controlled and prescribed burning may be, as there is essentially no risk in the structures in the interface, the cost makes this an impractical management style for more secluded sections of national forest, once again showing the demand for increased controlled burns instead. Even in easily accessible locations, the cost of these methods can be too much for the forest service to manage, so one reason move has been to sell sections of the national forest lands to local tribes, private businesses, private buyers, or other interested parties. A congressional bill entitled "John D. Dingell, Jr. Conservation, Management, and Recreation Act" from March 12, 2019 outlined a collection of sections of lands sold or transferred to reduce those burdens [35]. As nice as other methods may be, they still just are not practical on a large scale setting. The most effective current method of fire management is still preventative burning, and allowing wildfires to burn when there is sufficient evidence that the fire will not grow to threaten any important structures or communities.

2.3 An ever-changing climate

The United States is battling increasingly stronger fires for more reasons than just our poor forest management systems over the 20^{th} century. The Rocky Mountains and Western Colorado provide a unique geographical and ecological setting for fires to breed rapidly, abruptly, and dramatically. The landscape is classified as a desert biome in lower elevations, and an alpine tundra at higher elevations. Alpine tundras lack significant fire fuel due to the harsh climate and it is unlikely in the current state to see much fire activity, but the lower elevations provide optimal fire fuel.

While the weakened forests are certainly allowing the fires to burn readily available, easily burnable fuel, there are more conditions that are needed to allow a fire to spread. Primarily, for a fire to grow, the ambient temperature has to be sufficiently high enough with the water content of the fuel sufficiently low enough. Simply having a dead, overgrown forest does not mean that a fire is likely to start and spread, as is evidenced by Colorado forests during the winter. As humanity continues to see global warming and increasing extremes in climate conditions, the environmental factors that prime a location for a fire are going to become more common.

Currently, Eagle County allows prescribed burning so long as the county is not in a fire restriction period. They have more restrictions than just red flag warning for controlled burning, as controlled burning is less contained than other sources of fires, such as bonfires or charcoal grills. For the winter months, the fuel is (hopefully) covered in snow, or snow melt makes the timber too wet to easily spread to allow a successful preventative burn, as explained in the previous section. In addition, the reduction in temperature during cooler months reduces the spread of the fire as well. Ultimately, Eagle County is left with a small window of time in which the conditions to create a fire are sufficiently favorable to allow the fire to spread without being too favorable in which a fire becomes unpredictably dangerous. My hometown will continue to see snow up until early May, and in 2021 a forest wildfire had an ignition date of June 20^{th}. The fall does not provide a better season either, as the East Troublesome Fire in Kremmling Colorado wasn't started until October 14^{th} [36] That limits Colorado to roughly a month and a half between middle of October to late November, and early May to middle of June that provide decent conditions for controlled, preventative burning given the current ability to predict wildfire spread.

The Rocky Mountain Climate Organization (RMCO) is an organization formed to research and report upon the climate changes of the Rocky Mountain Areas. It looks at weather trends based on current emission levels, and potential weather trends if we reduced heat trapping emission levels. Given the findings, the organization works to propose solutions to better reduce the emissions, and plan for the natural disasters that are due to occur due to the change in climate [44]. In the summer of 2021, the group released a report titled "Climate Projections of Eagle County" [44]. The report outlined prediction in temperature, precipitation, snowfall, and the impacts of those predictions. It analyzed trends and patterns from the past century to make predictions in both current rate of emission conditions and reduced rate of emission conditions. The report looks at over 20 million individual predictions of high and low temperature to create prediction scenarios for 4 different levels of emissions broken into four different 20 year sections across the next century. The specifics of each of the conditions of the report are not important, but it is important to note that all 4 different emission levels predict the temperature increasing, and the days with extreme temperatures increasing compared to current observed conditions. The environment is only going to continue to exacerbate current fires and reduce preventative burning time.

CHAPTER 3

Costs of Fires

When studying wildfires and their effect on surrounding communities, it is important to look at the cost of the fire. Comparing the expected costs between different fires is useful in prioritizing resources to certain fires over others. In addition, by being able to effectively predict an expected cost, federal funding can be allocated appropriately to the areas that most need it. By determining the costs of different fires in different areas, as well as looking how they effect communities in the long run, policy makers in the federal government can also determine what areas of funding are lacking.

3.1 The true cost of a fire

The actual cost of a fire is not a specific, easily calculated variable. We can measure the amount of personnel, time and resources used to suppress a fire, and often those are the numbers used to report the "overall cost of the fire." But the true cost of a fire goes beyond simply the direct resources used to put it out. The cost includes the damage to the forest and ecosystem, effects on the wildlife in the area, cost of evacuations to individuals and the cost of lost business. In addition, there is the cost of the burn scar, or the effected soil left after a fire has been declared extinct. It is easy to put a number to the personnel and resources needed to ensure the area recovers safely from the fire, other costs are not as easy to calculate. For example, a common activity on a fire burn scare is mudslides, due to the decreased vegetation and dryness of the soil. If the burn scare is near a major road, that mudslide can impact travel. The road closures resulting from the mudslide may be only a minor inconvenience if there is an easy, accessible alternative, or may have devastating cost impacts if there isn't.

The Western Forestry Leadership Coalition, based in Lakewood Colorado, studied the cost of fires in the surrounding area to get a better understanding of how the total cost of a fire extends beyond the immediate sum often published in articles [16]. Their findings concluded that often the reported cost is limited to merely the cost of suppression and personnel. What they found is that often that cost is only 20% or less of the total cost of the fire. They broke the costs up into four categories.

The first category is direct costs. Direct costs include fire suppression costs, property damage costs, damage to utility lines, cost of evacuation resources and other easily calculated, directly related, and immediately apparent costs. In other words, the costs that are usually talked about when news articles and web pages refer to the cost of the fire. The most common direct cost to talk about is suppression costs, which include the cost of the supplies as well as the personnel related to the suppression efforts of a fire. The National Interagency Fire Center has a complete suppression cost breakdown available from 1985 to present [13]. There is minimal debate as to the total price tag of direct costs on each fire, as all costs have a monetary value.

The second is rehabilitation costs. Information to calculate rehabilitation costs are typically easily available and easily quantifiable, and often the funding for rehabilitation costs come from federal programs. The biggest distinction between direct costs and rehabilitation costs is the time frame. Rehabilitation costs can continue to accumulate years after the fire incident. Cost from the BAER, or burn area emergency response [4], are often the only costs associated as rehabilitation costs, as those tend to be the response immediately following a fire. However, costs extend to any funding to restore watershed, bringing back species in the ecosystem, and building up natural barriers that were damaged. Despite the actions needed in rehabilitation being easily quantifiable, often the actual rehabilitation price tag for a fire is underrated. One reason is that the effects of a fire on an ecosystem can get intermingled with other effects [21]. For example, if a fire damages a water supply, and then the following year a factory also leaks chemicals into the same water supply, it is difficult to say which costs are fire related and which costs are chemical related. Often, the costs will get grouped toward the chemical instead, reducing the conclusion of rehabilitation costs from the fire.

The third is indirect costs, sometimes referred to as impact costs. Indirect costs are typically not included in the reported fire cost, and not as easily to calculate. Situations that classify as indirect costs are loss in revenue or taxes, or a decrease in property values. They have a much longer lasting impact on the community, and typically do not have funding to assist with efforts such as direct or rehabilitation costs do. The California wildfires in 2018 came with a massive indirect cost price tag. One source estimates that the economic cost from the state totaled 42.7 billion dollars [51]. Outside of the state of California, those same fires cost an additional $45.9 billion due to disruptions in the supply lines between other states. During the Grizzly Creek Fire in Colorado, local hotels had to shut down, restaurants had to close, and tourists were unable to visit the location. The resulting cost was a decrease in revenue from the tourists and from a decrease in sales tax during a time when there is a reasonably high level of tourism. Other fires caused similar costs. The Caldor Fire in El Dorado County in 2021 was a massive forest fire that did not burn down a single structure. However, the effect of the fire was still detrimental to local businesses. One restaurant had to close due to evacuations, and then upon reopening saw fewer patrons than usually expected for late August. The expected cost from the short closure was over $10,000 [24]. None of the costs were covered by insurance, and should be classified as indirect costs. However, costs such as personal business losses are often not included or talked about in regards to the overall cost of a fire.

The fourth cost, and hardest to quantify, is the additional costs, sometimes called special costs. These are any other costs associated with a forest fire, and are typically more qualitative costs than quantitative costs. Life loss is included under additional costs. Sometimes there is a way to "value" that loss of life, such as looking at the funding a fire-fighter's family might receive, or the insurance payout from a debt, and other times it is completely subjective and not possible to actually calculate. Other indirect costs are health complications either from smoke, long term issues with the water, closure of transportation methods, re-direction of supply lines, loss to the ecosystem, aesthetic loss to a location, and loss of wildlife. Any long term effects a fire can have on the structure of a community, such as a reduced tourist season, closure of beloved businesses, or taxation of mental health can also be included here. Fires that threaten historic or natural landmarks can also claim a higher additional cost value. These are important, necessary, and relevant costs to consider. More often than not they are not included in total calculations, and that is primarily due to the difficulty in calculations.

It is not easy to state an overall cost for a fire, especially as the fire may continue to be costly decades after the initial burn, which makes measuring the "impact" of the fire more complicated than merely looking at a cost per acre or total acres burned, as has been the trend historically. After looking at a couple specific fires in the Western United States that were significant enough to yield more post-burn research into their impact, the Western Forestry Leadership Coalition found that "total expenses range from 2 to 30 times reported suppression costs" [16]. Looking the cost for the

2020 wildfire season, it is clear how the suppression costs and acres burned fail to tell the whole story. A weather forecasting company called AccuWeather has estimated the 2020 cost of wildfires could be between $130 and $150 billion dollars [42], a far different value than $2.2 billion dollar cost published on the National Interagency Fire Center page [13]. By understanding a more complete picture of the costs of wildfires, it becomes more evident how important being able to better prepare for them, and better reduce their intensity is. If efforts can be made, however costly they may be now, to ensure that future wildfires do not burn for as long or as severe, costs in the long run can be saved. The addition of the indirect and additional costs highlights the high price tag that currently comes from such destructive natural disasters.

3.2 Benefits of Proactive Burning in Cost Reduction

Many of the costs listed above can be reduced, or even eliminated, with proper proactive fire prevention methods. If fires are started with a pre-planned containment, the cost of fire suppression becomes minimal. pre-planned fires can be started in locations that either consist of natural containment lines, such as a road or a river, or artificially created containment lines, such as a cut down section of forest or an already burned section. The containment lines can use more time consuming, but ultimately less costly, alternatives to helicopters desperately trying to lay enough fire retardant to suppress the fire. In addition, the timing of the fire will reduce costs as well. These fires can be started in optimal conditions so there is minimal need to do much fire containment in most directions of the fire. The fires are then allowed to burn to completion so there is no need to spend significant money or resources on putting out the fire. In regards to rehabilitation costs, the fires can be burned at a time in which there is minimal threat to surrounding structures. In addition, the time of the year can be chosen such that the intensity of the fire is significantly less, which will reduce the burn scare afterword. By lighting fires at times where healthy trees are unlikely to become a blaze, the fires will burn through the dead fuel quickly but at a lower temperature, leaving behind healthy nutrients without drying out the soil. As a result, the fire area will have no need to later qualify for Burn Area Emergency Relief funding, as the burn area will be minimal.

The area that proactive burning can most sufficiently reduce the financial impact of is in the category of indirect cost. By planning out locations, times, and duration, fires can be planned to have minimal interference with businesses, property value, tourism or other sources of indirect costs. Communities can be made aware of the efforts, and times to burn can be decided in a communal decision. In addition, due to the proactive fire being planned and contained, there is no need to have evacuation orders or travel restrictions in place that would effect day to day life.

There is a potential for controlled burning to have long term health effects just like a wildfire could, because it does ultimately release ash and soot into the air. Unlike a wildfire, however, typically controlled burns happen in a small enough scale, on days with calm enough weather, in a climate that encourages less quick burning, smoke creating, flames that the impact here is minimal. It is impossible to eliminate all risks associated with a wild fire, as controlled burns and wildfires do the same processes in the end, but much of the cost of wildfires has to do with the extreme nature, whereas controlled burn allows more control and planning over the conditions.

Despite the obvious benefits listed above, there are some strong costs associated with the decision to participate in proactive burning. The debate over the actual benefits is likely not going to end anytime soon. One of the primary issues is that only a small portion of the forest space in the United States is likely to burn each year, so the research into what sections of the forest would most benefit from proactive burn is highly costly, without a set aside governmental fund to help. In addition, efforts to participate in proactive burning on a substantial enough scale have not existed for enough time to actually analyze. While proactive burning is common in farm management, the effects it has on a forest at preventing catastrophic fires simply does not exist to be studied. Simulations over the years have been proposed for different geographical regions, such as a large scale study in Australia. However, the data provided to create said simulations is still lacking. The study was published in 2020, in which they found that different geographic regions appeared to benefit from different types of proactive burning. The most beneficial to areas appeared to be proactive burning that focused on proactively burning the edge of the wildlife urban interface, rather than thinning out entire sections of forest [39]. One drawback of the study is that it focused almost entirely on the cost balance of proactive burning vs. a wide scale fire. Again, only a small portion of forest in the United States does evolve into a wide scale wildfire, so effectively preparing for all possible fire positions would likely be less cost efficient than trying to fight the fires as they happen. But when looking at factors beyond just the monetary costs, such as the additional costs, different methods may be found to be more effective. There just is not sufficient research yet to effectively draw a conclusion, which is why the United States has not put forth significant effort to create a large scale proactive burning movement.

CHAPTER 4

Simulation

According to the Merriam-Webster dictionary, a model, specifically mathematical model, is "a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs: also, a computer simulation based on such a system" [37]. In the most basic sense, any mathematical conclusion based on data is classified as a model. Data is a broad term representing information. It can be information subconsciously observed and then later recalled mentally, such as an image of a place, or it can be carefully controlled and recorded information about supernovas in space. The first recognized models were simply counting and recording the results on something. These models were found as early as 30,000 BCE via marks carved into a bone. From there, depictions of astronomy and architecture were modeled around 4000 BCE. As human civilization continued to advance, the field of mathematical modeling did as well. By 2000 BCE algorithmic models were used in advanced civilization to help shape daily life patterns. In 600 BCE, Thales of Miletus used mathematical modeling to predict a solar eclipse, and developed a relationship between people's shadows and their height's, an activity which is often done by middle school students in modern day classrooms. As the knowledge of the time increased, and the computational ability to derive conclusions from that knowledge increased, the field of mathematical modeling continued to increase.

The most significant advancement in mathematical modeling was the creation of the computer. Prior to its creation, all models had to be created and calculated by hand. In the early 20^{th} century, workers across the world were used to do just that, running algorithms by hand to calculate the results. They were often called "computers" as they were computing the solutions [46]. The first computer was designed in the 19^{th} century, called an analytical engine. While it was never successfully built, it provided the groundwork for automating calculations in a way that allowed for re-programming to do different calculations on the same machine [22]. From the analytical engine's design, the first true programmable machine, the ENIAC, or Electronic Numerical Integrator and Computer, was created. Work on the ENIAC started in 1944 and was completed in 1946. It was designed to be used in the military to provide battlefield calculations during World War II, and while the war was over by the time construction ended, it still played a role in the calculations needed for the creation of the hydrogen bomb. The machine could do up to 5,000 additions in a single second [23], far out-preforming what any one individual could calculate. The machine opened the doors for more complex mathematical models that could be used to do more than just strait calculations. It shifted the goal of mathematical models from describing situations to solving indescribable situations instead. Since the creation of the ENIAC, the field of modeling has grown as the computational ability has grown to open more doors and possibility of modeling, creating a positive loop of expansion.

In today's society, modeling has expanded to much more than just observing the world, and determining simple relationships. Modeling today can be used to describe the world, take in information to make decisions, such as in autopilot cars, communication systems, and much more. Despite the increased complexity and applicability of mathematical modeling, the foundation remains the same. Gather data, make inferences about the data to build the model, use the model to determine new information. Most mathematical models return primarily numerical information that can bet used to represent qualitative or non numerical results.

Other forms of modeling can be represented visually. Sometimes the desired outcome of a model is not necessarily something that can be represented as a data frame, but a more visual or animated result. Creating a model using the relationship of predictor variables to predict a situational response is not as practical when trying assigned names or numbers to actions, movements, or interactions. To represent more visual or situational models, one can look to running a simulation. The key factor that defines a simulation is the the quantity of situations analyzed. Often, models are run once on a set of data to give a result, whereas simulations are run multiple times. The data gained from running the multiple simulations are then aggregated and analyzed to make final conclusions. Simulations can re-create many different types of scenarios or situations, and are widely used to do so, built off of many different calculated model results acting together based on the information from previous calculations. They still rely on some prior knowledge of predictor variables to impact the result of the simulation by providing situations for each step of the simulation, such as probabilities, calculated direction or reaction responses, or a list of possible reactions corresponding to different likelihoods. Many of the calculation steps are repetitive, and to calculate by hand would be unnecessarily time consuming. Instead, programmers can make a simulation that runs through many steps almost instantaneously, taking information gathered from each step to build the next step without someone needed to hand calculate and respond. Simulations can also help researchers preserve variable information through a process. While solving multiple equations on a computer is not as difficult as it once was, keeping track of 200+ variables can become very difficult even if the calculations themselves aren't, often leading individual calculations to be more simplified than the thing they are calculating. Simulations give a way for a program to manage all the variables that may be needed and then only report the final "important" variables.

One specific example of where simulations and modeling can preform what strait calculations cannot is in predicting the shape of proteins. According to a chapter in "Fueling Innovation and Discover: The Mathematical Sciences in the 21st Century" published in 2012 by the National Research Council and National Academies Press titled "Mathematical Simulations: When the Lab Isn't Big Enough," it is not possible for a person to determine the shape a protein will fold into based on the chemical formula. There are too many factors to calculate. However, simulations are providing a method to come close to predicting shape and shape changes [1]. They do this by running multiple simulations, likely over 1000, and analyzing the end result to see what is the most likely outcome. Each step of the model was approximated and coded into the simulation, and then the simulation ran through the algorithm, running each calculation numerous times, and then using the results to make an informed prediction on the shape that would be nearly impossible to complete by hand. At the core, it is still just a model where the program used automatically transforms the numerical results into a visual image, and the simulation aspect comes from running the model repeatedly to get a collection of potential shapes.

Even now, simulations cannot preform any better than a good approximation for many of the more complicated processes of life. The limitations are both on a mathematical model limitation and a computational software limitation. The models coded into the simulation are still approximations based on the information available to researchers at the time. Simulations cannot outperform the limitations of knowledge available, but improvements to simulation ability, both time and scope, are being developed constantly to keep up with improvements in knowledge in different fields that use simulations.

Most simulations rely on a certain amount of regulation to the randomness as it is impossible to truly code randomness. It is possible to code pseudo-random numbers, but impossible to code actually random numbers. Beyond just that limitation, humanity is not at a level either computationally or applicably to truly put randomness into simulations and modeling. Examples of the limitations of randomness include assuming a levels of homogeneity, excluding external factors from the discussion, and eliminating the role the environment may play on a situation. While the models can be reasonably accurate despite those limitations, they still can only provide an approximation of what may happen, and thus are limited in their scope of application. They can be used to make informed decisions, and predict possible situations, but no model can predict exactly what is going to happen, as the knowledge is just not there yet.

Another good situation to use modeling is in travel patterns. Simulations can be used to model travel patterns of large groups of people around the globe based on already known trends. By looking at patterns of larger groups of people, the data trends towards similar patterns and the individual variation becomes negligible. These methods would be useful in predicting passenger patterns of the Christmas holiday based on travel patterns from the Thanksgiving holidays and relationships in the past, but would be much weaker at predicting people for one specific flight from LaGuardia to LAX on Christmas Eve. Common simulations do not necessarily account for the more "random" aspect of human decision making, such as getting in a car accident or missing a connection. Once again, it is limited by relying on a certain level of predictability to run the simulation. Just like Central Limit Theorem in probability can be used to make general assumptions about certain conditions of the population, but tends to preform poorly in small sample sizes due to increased variability, common simulations do not preform as well with higher heterogeneity.

There are many aspects of the world in which the things we want to explore are not suited to traditional modeling or simulations. Situations include those which do not appear to be governed by defining differential equations or complex conditions.

Instead, the situations might be governed by their elements following a set of rules instead. To address those, the field of Agent Based Modeling and Simulations, ABMS, came into existence. Agent Based modeling is a newer field of mathematical modeling and simulation, as it relies on increasingly complex computational abilities compared to other forms of models, and thus would have been limited by computer technologies [31]. It allows for a greater level of "randomness" and heterogeneity within the elements of the model. Using agent-based modeling allows for probabilities to change based on other factors of the simulation. One comparison between classic simulation and agent based modeling simulation would be calling them "microscopic modeling" and "macroscopic modeling." Classic simulations look at the larger scale patterns, while agent based modeling is typically more focused on the small scale interactions between components to tell the larger story instead [11]. Classic simulation has each component included in the calculations and algorithms that make up the larger model, whereas agent based modeling uses those small components to dictate the behavior of everything around it. In addition, classic simulations use large scale differential equations or quantitative analysis to define the behavior of the simulation. In contrast, an agent based model can see the impact small actions have on a larger scenario instead. Using those impact, the findings of the simulation could lead to defining these differential equations instead. Both types of models and simulations are useful, important, and applicable in today's world, depending on the subject type and the information available about it. However, I will be focusing on agent based modeling for my project.

The most unique aspect of agent based modeling compared to other systems of modeling is the ability for the model to allow interactions and "choices" to be made given certain situations. It accomplishes this by creating agents, and subsequently giving them rules. The actual definition of what constitutes an agent is complicated and not universally agreed upon. Some mathematicians argue that an agent is simply anything that can "make decisions" about what to do given a certain situation. Others argue it goes beyond independence and requires the agent to both have rules it follows, but also be able to learn and adjust those rules based on the environment. Regardless of the specific definition, the important part about agents is their ability to "make" a decision based on information available to them in the simulation, and thus equations can be altered for each specific agent. According to Eric Bonabeau in his article "Agent-based modeling: Methods and techniques for simulating human systems," agent based modeling is useful and should be used when the actions of each agent is reliant upon the action of the agents around them, and not uniformly identical. In addition, ABMS is useful when there is a high degree of heterogeneity in the population that is important to preserve, and when the agents can learn and adapt from the information around them and through their interactions [11].

One of the biggest issues with agent based modeling is the ability for unnecessary complexity to be included in the model. It is easy to code in behavior from the agents to act a certain way because the coder thinks that is what should happen, which creates a model with a higher degree of complexity. Without sufficient justification of the behavior, the model becomes less reliable and less applicable. In addition, as is often the case when modeling human behavior, agent based modeling relies on coded probability or rules to simulate random human behavior. Without the proper paramaterization of these rules, the results once again become hard to apply [11].

The official origination of Agent Based Modeling is unclear, as models that are classified as agent based models appeared before it was widely recognized. Some of the first agent based modeling programs developed from an economical modeling frame, with an effort to combine macro and micro economics. At the same time, models were developed in social sciences to study human interaction patterns, in biology to study epidemic spread, and in many other areas of research. One of the first models published to use an agent based approach was published in 1971, which was a model of segregation in which the agents of the model segregated themselves based on defined rules. Rather than a larger equation dictating the conclusions, the agents reactions to each other based on the rules yielded unexpected results. The model used is a general model of segregation in which any identification, whether race, sex, age, education, or other defining characteristic, can be the instigator for segregation. Findings from the model were used to analyze what percentage of the "minority" population is needed to cause a "majority" population to leave an area as both groups try to surround themselves with people that reflect their own identity [45]. But it wasn't just social sciences that saw the use of agent based modeling emerging to study behavior. The believed first true agent based model was derived for biology modeling apply game theory ideas to biological situations to model evolution and Darwin's theory [26], however there is no way to confirm the claim.

Even within the arts and animation side of computational sciences, agent based modeling has deep roots. Craig W. Reynolds created a bird simulation model using agent based modeling practices in 1987. The simulation is called Boids. Reynolds had an objective to model bird flight to create flight patterns. In his model, his agents were birds and they had three rules. They had to avoid crashing into any other bird at all costs, then they had to match the speed and direction of the birds around them, and finally they had to cluster their flock [41]. At the time, the officially recognized field of agent based modeling wasn't fully established. His findings concluded that simply using those rules, relatively normal and common looking flocks were created without a "lead bird" being used to organize the flock in any way. Instead, each bird was an individual agent, capable of making decisions independently, and creating a flight pattern [10]. Other conclusions from this model were related to the predictability of the flock. The simulation showed that there was enough complexity with only those three rules to make it nearly impossible to predict the long term behavior of the flock, however predicting short term sections was reasonably simple.

4.1 Introduction to Net Logo

Agent Based Modeling has been used in enough different areas of study for long enough that there are multiple programs created to run agent based models. Three popular platforms exist. The first is CORMAS, or Common-pool Resources and Multi-Agent Systems. It uses a programming language of Smalltalk, and is used to simulate social and biological models. A second platform is REPAST, which stands for RE-cursive Porous Agent Simulation Toolkit. It is open source and free to use, and designed primarily for social sciences. Both CORMAS and REPAST use object oriented program. A third is Net Logo, which is arguably the most common. It was designed for educational purposes, and the interface for using it is much easier than the other platforms. In contrast to the first two programs, Net Logo does not use object oriented programming. There is no program which is considered the "best" program. NetLogo is likely the most accessible of the three programs, as it is designed to be used in an educational setting without needing exceedingly high levels of computational ability. In addition, there is an online version of NetLogo as well. In contrast, REPAST is recommended for computers equipped with higher than normal computing powers, or cluster's of computers rather than an everyday computer the average undergrad student may have [7].

The specific program I use for this project is NetLogo. The founder originally created a program called StarLogo in 1989. At the time, it was created for one specific computational machine at MIT. As computational ability grew, so did the program. In 1999, NetLogo was created out of StarLogo, with NetLogo 1.0 released in 2002 [2].

Within Net Logo, there are four types of agents: turtles, patches, links and observer. Turtles are small agents that are allowed to move around the screen. Patches are a set locations on the screen. Links are connections between two turtles, and the observer is similar to the programmer in a sense that it asks the other agents to do certain things. Turtles and patches both have traits and characteristics that define them. Some are easy to see, such as color, velocity, or size. However they can also store information such as a magnetic polarity, or a preference to turn right. In addition, turtles and patches interact constantly, and turtles can access the information of the patches it is actively standing on or near. They use the traits stored within the agents to make decisions based on their interaction as to what the patch or the turtle will do in response. Common ways to use turtles and patches is to make turtles people, and patches resources. When a turtle stands on a patch that is assigned the resource of water, the turtle now contains water as well. In addition to the turtle-patches interaction, turtles can also interact with each other. For example, if two turtles are headed in position directions on the same line, they can collide which may create a new interaction. The links allow for the turtles to connect with each other, and has some information attached to it as well. When running a social science model, links could be used to represent familial units. While each agent makes their own decision, the link can be used to ensure that familial units makes similar decisions to each other [56]. Each step of an agent based model is done within a tick, which is just a one unit measurement of time. On each tick, the program runs through the code, preforming each line one at a time, and then when it cycles through the code it will increment the tick and do it again.

Due to the complex, interactive nature of an Agent Based Model, the ability to re-create an identical result between two programmers is minimal. Bajracharya and Duboz compared the similarity of NetLogo, REPAST, and CORMAS by running all three programs with an epidemiology SIR (Susceptible, infected, recovered) model of infection spread. They created the programs as similar as possible, and gave the same initial conditions. Once they obtained the results from running 30 simulations, they found that there were significant trends of dissimilarity. In particular, REPAST and CORMAS gave very dissimilar results, while NetLog and CORMAS gave the most similar. Once again, the trend proves the reduced ability to identically reproduce results when running agent based models, even when given nearly identical models and rules to run. Due to that difficulty, it is necessary to justify each aspect of the agent based model code and report all decisions used.

I have chosen to use agent based modeling for my fire project for two different reasons. The first is that lack of reproducibility. I am looking at how different variables effect the shape, spread, speed, and intensity of a fire rather than trying to predict exactly how a fire will look in a certain situation. The moment specific factors which determine how and when a fire spreads are so random that trying to accurately and specifically determine where one fire is going to spread is impractical given today's simulation ability. The second reason I am using agent based modeling for fire simulation is the agent oriented nature of the program. Complex empirical models to predict fire spread have been used for decades, however they are often limited by the the fire data available at the time, which is limited to the forest and environmental conditions at the time [33]. Their scope to predicting fire spread in future years, in which we are likely to see more drought, more extreme environmental conditions, and a possibility of new infections within the forest population, are not easy to include into these models. However, they would be significantly easier to include in an agent based approach, as that can be easily modified to look at different locations and environmental situations.

CHAPTER 5

Agent Based Modeling of Fire Spread

To start my simulation I began with the fire model included in the NetLogo package. It was created by Uri Wilensky, the co-creator of the entire NetLogo program, in 1997. It is a simple fire spread model over a limited simulation space, with an easy to use interface and visual. The focus of the default fire model is to explore how the density of the simulation space effects the ability for the "fire" to spread. The simulation space is representative of an expanse of forest, with the borders of the simulation space being equivalent to the edge of the forest. The simulation comes equipped with a setup button, which I will explain more in section 6. In a simple summary, the button sets the distribution of trees across the simulation and creates the fire line start. The other button is the go function, which actually runs the simulation. Again, I will explain in more detail the structure of the simulation later. Percent burned monitors the percentage of green patches that "burn," turning into dead patches, and returns that value.

The simulation runs by following a system of commands on each cycle, or tick, of the simulation. On each tick, the "go" function, which can have any name, not specifically go, will run. The function will be comprised of a series of statements that work by "asking" the agents to do something, such as asking turtles to move, or patches to change colors. The agents don't necessarily have a choice, so asking is a weird terminology, however it exists none the less. If the function has a step that asks different agents to do something, the simulation will randomly select an

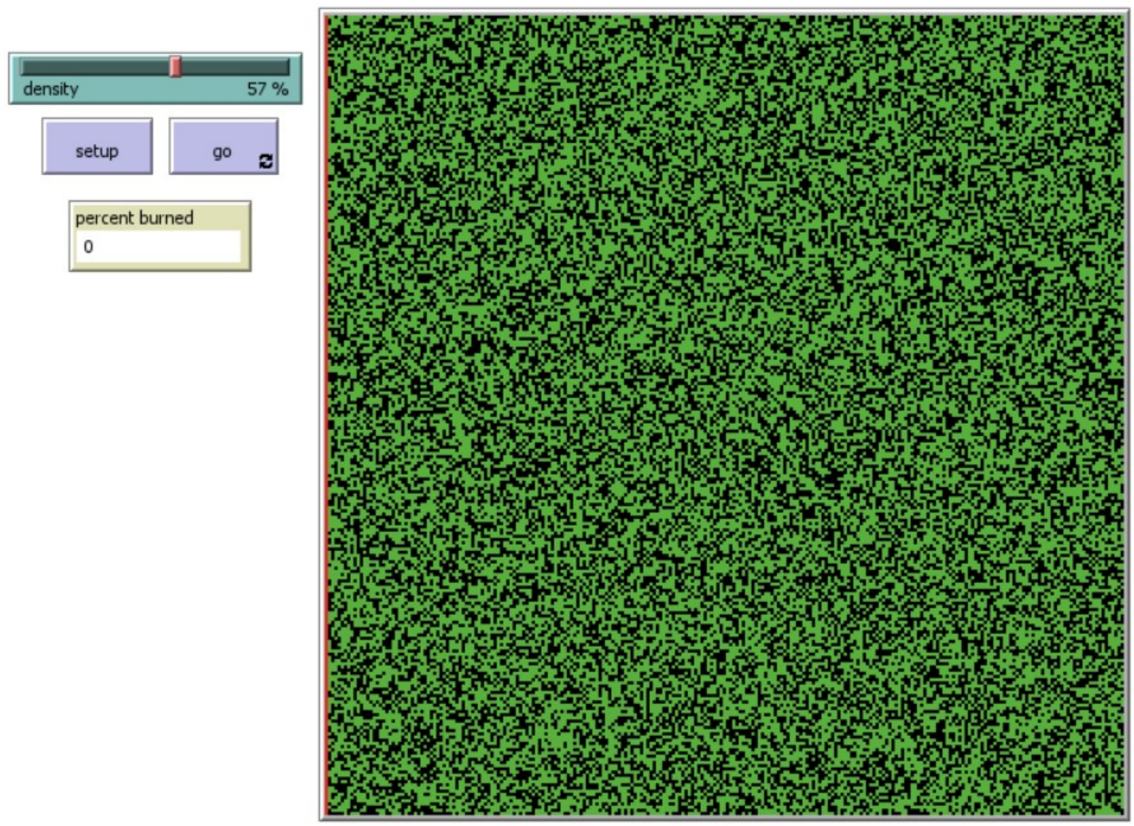


Figure 5.1: Base Fire Model Created By Uri Wilkensky, 1997

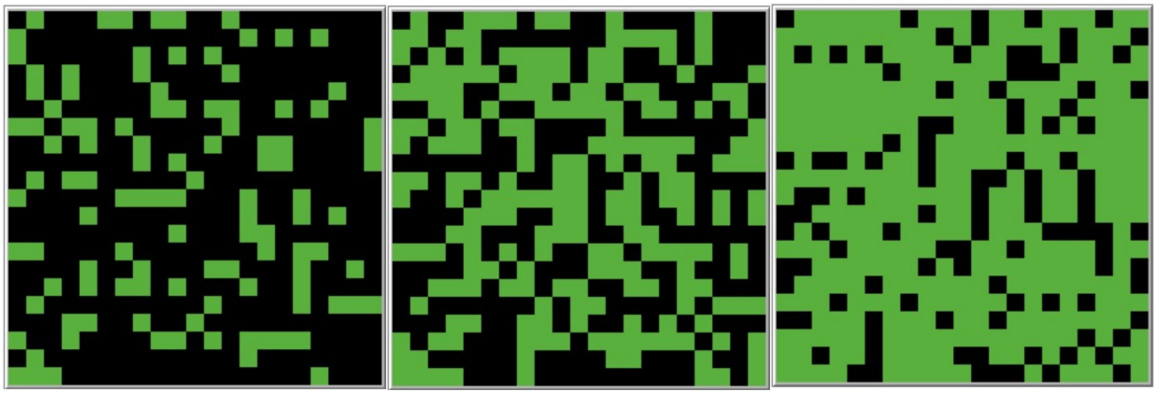
order of the agents to ask, which helps keep a random aspect to the simulation. For example, if there are a list of 10 agents that are all asked to move forward one "step," the simulation may ask in order of top to bottom, or left to right, or may ask in a random permutation of the 10 agents.

5.1 Agents

As with any agent based model, the simulation foundation can be broken up into the role each of the 4 different agents defined in section 4.1 play in defining the simulation: patches, turtles, links, and observer. Not all 4 agents are needed in every model, as is evident by the lack of link agents found within the fire simulation model. In addition, the role of the observer agent is simply to record the information, so it plays a non-essential role in this model. The role of the observer can be thought of as similar to the role of a programmer instead, running the simulation rather than shaping the simulation.

5.1.1 Patches

The simulation space of the fire model is built upon the set up of the patches. They are representative of a smaller section of the forest, which in this case I will use to represent a "tree," if the patch is colored green, or a section without a tree, if it is black. A sample of a 21 by 21 unit simulation screen is shown in figure 5.2. It is easy to see how the different density settings change the landscape of the simulation space, with the forest in 5.2.a having more black patches, or patches without a tree, than green forests, or trees. The middle landscape has an even mix of green and black patches, and the 75% landscape has predominantly green patches in the simulation space. The actual simulation space I use consists of 501 by 501 units, rather than 21 by 21, but is simply a larger scaled version of this smaller simulation



(a) 25% **(b)** 50% **(c)** 75%

Figure 5.2: 20x20 Simulation Space at Different Densities

space. The simulation space could easily be conceptually expanded to represent a larger forest, in which the patches may represent a certain density of trees rather than individual trees.

5.1.2 Turtles

The turtles of this model are the agents that cause the fire to spread and burn across the forest space created by the patches. They are the most "lifelike" in that they could have the ability to move, breed, spawn new turtles, or die. This model has two types of turtles, fires and embers, which each have their own role in the simulation. The first, and more important agent, are the fires. They are represented by a bright red square with a thin black border, which can be seen along the left side of figure 5.3. Within this simulation, the fire turtles do not actually move, instead they spawn new turtles in sections of forest around them that is available. In essence, each fire turtle has the ability to spawn a new turtle on any of the surrounding green patches. They do this by asking a green patch to breed a new turtle on that patch. When a new turtle is created, it will be breed as a fire as well. Only the fire turtles have the ability to propagate new fires in surrounding patches of forest, or asking the

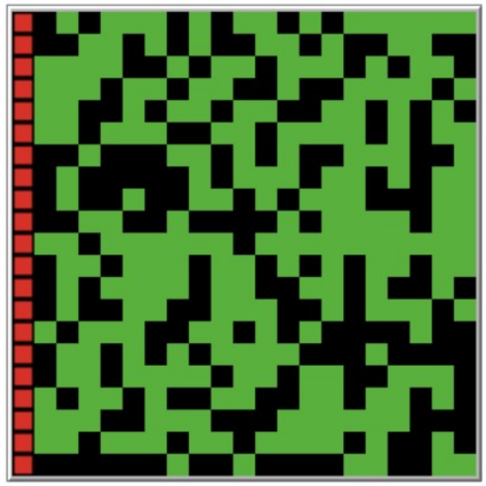


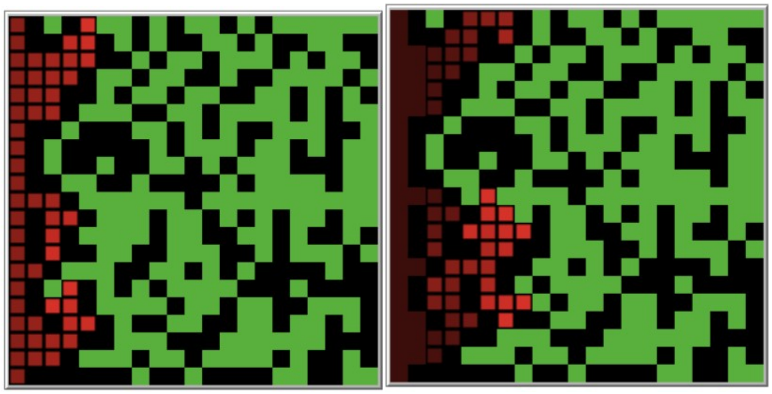
Figure 5.3: Line of Fire Agents

surrounding patches to spawn a new turtle. This is as if the fires were creating sparks that may or may not turn into fires.

At some point, the fire turtles will become embers instead. In the base model, the fires become embers after each tick. Embers are counted as active hot spots of fire, however they do not have the ability to create new sparks in neighboring patches, and thus are unable to propagate more fires in other patches. They are a darker red than the fire turtles, and slowly fade to a deep maroon, at which point they die out entirely, leaving the patch a maroon color. Comparing figure 5.4.a and figure 5.4.b, both have the leading edge of bright red fire turtles, followed by a section of darker red ember turtles. However, figure 5.4.b has a section of patches following the turtles, which no longer have the black border, representing burnt patches that do not have either a fire or an ember turtle present on the patch.

5.2 Expanding the Model

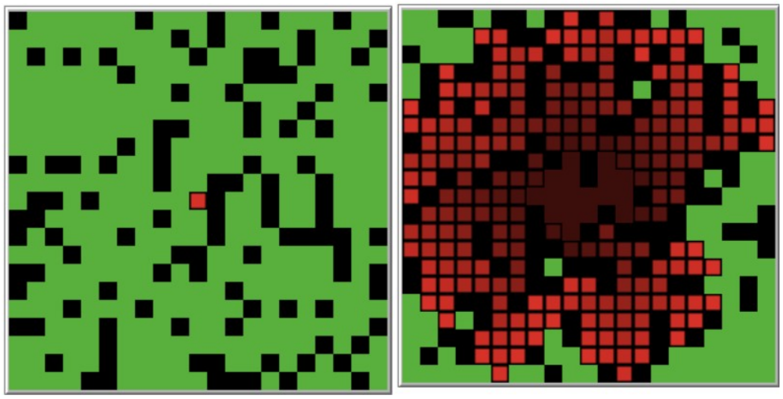
The first step in expanding the fire model was to address the assumptions of the base model and decide which assumptions I wanted to address, and which assumptions were appropriate to make. The first assumption I noticed is that the fire can spread



(a) 3 Ticks **(b)** 4 Ticks

Figure 5.4: Ember Agents

equally in each direction, with a default of each turtle asking it's north, east, south, and west neighbors to burn. Wind speed and direction are ignored, which are two important factors in fire spread. In addition, it assumes that if a patch gets asked to spawn a new turtle, it does so with no variation in probability. As the climate keeps getting warmer and dryer, and our forest keep dying, we get closer to this assumption becoming reality, however today there is still some limitations in whether a spark can cause a tree to light. A third assumption used in the model is that each green patch is identical, and thus will behave identically. For future exploration, this could be addressed by adding patches of different colors that have different characteristics, however I will not be including this within the scope of my project. The model also uses the assumption that once a patch catches on fire, it cannot be re-lit. I will be keeping this assumption, although there is always a chance of back burning in a wildfire. Even if there is back burning, it will die out quickly as the primary fuel source has been used up already, so it is appropriate to ignore this. A final assumption is that patches have a consistent level of extinguishing, in which each turtle dies 12 ticks after breeding. I will also be keeping this assumption, as similar to the previous one, the amount of time it takes for one section to burn out completely will not effect the total predictability of the fire model. If it does happen



(a) Origination Point **(b)** Full Simulation

Figure 5.5: Base Simulation

to create a second spark, there will not be enough fuel sources available to support a new fire, so thus is not worth considering in the scope of this IS project.

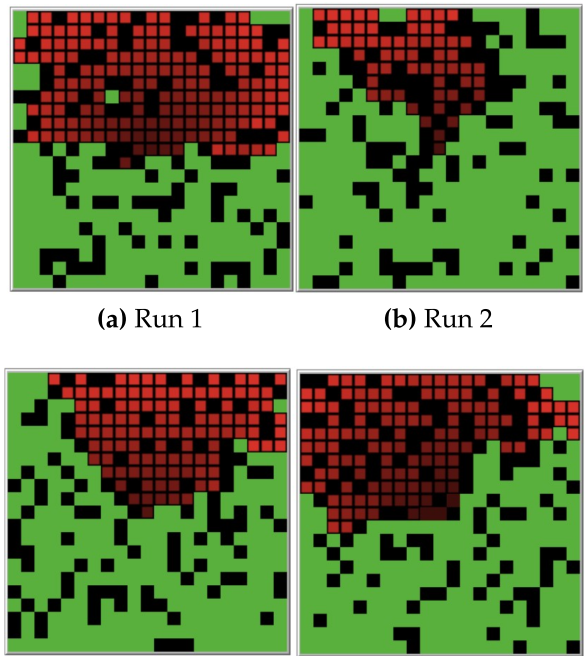
As I go through the set up of my simulations, I will be addressing these different assumptions, as well as addressing other changes to the code that I made. To begin setting up the simulation, a subset of patches, which corresponds the density of the forest, are randomly selected and turned green. The patches represent the sections which have trees that have yet to be burned. I have chosen a density value of 75%. While rather arbitrary, a density of 75% has a patch spread that allows for some open space to occur, yet still dense enough to allow most fire models to spread without having to have so many turtles asking patches to ignite that my computer gets overwhelmed with the simulation. An example of a section of simulation with a density of 75% is seen in figure 5.2.c. The next set up is to spawn a new turtle on a selection of patches. Since I am trying to model the spread of either lightning fires, or planned fires, I have the origination from a single point in the center of the simulation, as seen in figure 5.5.a. While this is zoomed into the center of the simulation space to be easier to see, it does accurately represent the way in which all of the proceeding simulations will begin. From there, the fire expands outward, until reaching the edge of the simulation map. A sample of the simulation stopped about 3/4 of the way through can be seen in figure 5.5.b. Further simulations could increase the size of the ignition point to be a small line, or a large line, which could represent different types of controlled burning. I will be leaving it as a single origination for my simulations to reduce the computational load on my computer, and reduce the number of factors that could be modifying the simulation results.

Once I had a more radial fire pattern, I decided address the first two assumptions about identical fire spread in every direction. I used completely hypothetical wind spread prediction patterns to get a better understanding of how the model works. I later used a similar principle for the wind spread pattern of my final model. An example of a hypothetical model is shown in table 5.1, and a corresponding visual of the simulation given the conditions is shown in figure 5.6.

0.8	1.0	0.8
0.5	Agent	0.5
0.1	0.0	0.1

Table 5.1: Hypothetical North Wind

In table 5.1, the fire will always ignite the patch directly above it, usually ignite the patches diagonally above it with a probability of 0.8, sometimes ignite the patches to the left or right with a probability of 0.5, rarely ignite the patches diagonally behind it with a probability of 0.1, and never ignite the patches directly behind it. It is important to note that each active fire will ask the 8 points around it, so a patch of forest may be asked multiple times by different fire agents. Simply because an agent does not have a sufficiently high probability to ask the patch behind it to burn does not mean a second agent later will not be able to successfully ask said patch to ignite. This pattern could mimic the effects of a northerly wind. To implement this, I used the "at-points" function, which asks the patches at a certain point away from the turtle. For learning purposes, I focused on only the 8 points immediately



(a) Run 1 (b) Run 2

(c) Run 3 (d) Run 4

Figure 5.6: Hypothetical North Wind Pattern Simulation

around the fire (turtle) location. Once I felt comfortable having the fire expand in different directions, I added in code to change the probability the fire spreads in certain directions, which better simulates the impact wind may have. As a result, I shaped the fire to better mimic a wind pushing it in a different direction, away from the center point. To get the probabilities of each patch of the simulation being ignited, I used a random number generator, so to code a probability of 0.8, I put an if statement that if the random float between 0 and 10 is less than 8, ignite the patch. Otherwise, allow the ember to fade, and thus have that section of the forest "burnt".

As seen in figure 5.6, each of the 4 simulations burns a little bit differently, yet they have a couple unifying characteristics. All four runs burnt in an upward direction, with all patches directly above the ignition point being turned into a fire. In addition, none of the simulations had much back burn. Figure 5.6.d had a little bit of back burn on the left hand side of the simulation. The landscape played a roll in the simulation as well, as the fires are unable to ask patches farther than one unit away to burn, so any section of green patches separates by a line of non-green patches will have almost no chance of burning, as seen in the shape in figure 5.6.b.

Once I had a decent understanding of how the fire model worked using hypothetical wind probability values, I decided to approach it in a more equation based manner. The rest of the assumptions from the base model remained. Including them would introduce more factors into the model, and reduce the ability to isolate the variables I am specifically interested in. For future modeling, the would not be extremely difficult to include if the need arose.

Having addressed all the assumptions, and having learned how to include them into the model, the next step was to determine which factors I was interested in looking at, and what equation I was going to use to relate them.

5.3 Simulation Variables

The National Weather Service states: "A Red Flag Warning means warm temperatures, very low humidities, and stronger winds are expected to combine to produce an increased risk of fire danger." [52] When Red Flag Warnings are issued, most fire activity is required to stop in order to prevent spread, so the variables they identify as being significant appeared to be a reasonable place to start. Different communities have different numeric factors for each condition [27]. Often a red flag warning will extend of a period of days or even weeks, rather than just a set amount of hours when the conditions are present. When a Red Flag Warning is issued, any and all open flame are not allowed outdoors. This includes smoking, campfires, charcoal grills, combustible engines, or any other activity that could potential lead to a spark and create a fire [52]. Based off the Weather Service's definition, along with conclusions from other readings, I have chosen to focus on the following four variables:

- Wind: Both speed and the direction it is moving
- Distance: How far away a section of forest is from the current fire, or how far the patch is from the turtle asking it to ignite
- Combustibility: How likely a section of forest is to burn

Since my project is more structural, theoretical based, my units for wind will just be patches per tick, and distance will just be patches. Wind will be coded into the Net Logo program by breaking it up into the x direction value and y direction value, which together make a 2 variable vector. The simulation interface gives the user easy ability to change the values, and thus create fire patterns in different directions. The wind variable will be a two dimensional vector called $\vec{w}$.

Distance will be the absolute value of the distance the potential patch of forest is from the source of the fire, or the current fire turtle that has the potential of propagating new turtles. While the distance could theoretically be any value, this simulation has it limited to within 5 x-units and 5 y-units of the turtle due to the computational ability needed to run the simulation. However, that still gives a spark 99 patches that it can ask to ignite per tick, which is a lot of opportunity. The value of the distance will also be stored as a two dimensional vectors, $\vec{d}$.

Combustibility is a broad term. In this case, I will treat it as the probability that a patch will burn given a spark lands on that patch, from 0.0 to 1.0. Conditions that could impact fuel combustibility in the real world are moisture levels, ambient temperature, ambient humidity, the fuel type, the age of the fuel, and other, more extreme factors, such as if the tree has been effected by beetle kill, if the overpopulation of the forests is making the tree weak etc. There are may different factors to consider when deciding the combustibility of a specific section of forest.

While I will not be directly including them, I will be able to make conclusions such as extreme combustibility causes extreme fire behaviour, even in low wind situations, which is why it is imperative that controlled burning be implemented safely and effectively. Combustibility is represented by a variable logically called c.

The variables will work together to shape the fire spread, size, and intensity in each simulation. They will do so by creating a probabilistic relationship of ignition for each patch.

5.3.1 Fire Propagation Probability Equation

To actually create the relationship that defines the fire spread, size and intensity, I have created a probabilistic equation. The equation will be used to decide with what probability the specific patch will ignite. Once again, as explained in section 5, the fire will ask the surrounding patches to ignite so long as the random number generator generates a value less than the probability. A base probability equation for the ignition probability function is given below:

$$P(\vec{w}, \vec{d}, c) = \frac{1}{1 + e^{-L(\vec{w}, \vec{d}, c)}} \tag{5.1}$$

Since it has a probabilistic structure, it has the following limit characteristics:

$$\lim_{L \to -\infty} \left(\frac{1}{1 + e^{-L}} \right) = 0$$

$$\lim_{L \to \infty} \left(\frac{1}{1 + e^{-L}} \right) = 1$$

These two limits are important in ensuring that the probability of ignition is not negative or greater than 1.

From there the next step is to define $L(\vec{w}, \vec{d}, c)$. Wind speed has a positive relationship with the probability of ignition. A higher wind speed increases the probability of burning. The angle between the direction of the wind and the location of a potential section of forest will allow for the wind speed to have a weak impact on patches orthogonal to the direction of the wind and no impact on the patches in the opposite direction of the wind. Distance has a negative relationship, where patches farther from the ignition point decreases in likely hood of burning. Combustibility will be the most important variable, with a positive relationship. The y-intercept of L is a negative value, since plugging in values of 0 for all the variables in L should yield a probability value close to 0, rather than an L value of 0.

Within the L function, there are two smaller functional relationships. The first I will define as A. A is the relationship between wind speed, wind direction and direction of the patch. A will use a vector w representing wind speed in the x and y direction, and p being a vector representing the location of the patch of forest being asked to ignite in relation to the patch of forest with the spark. The result of A is a scale factor of the wind speed for that specific patch of forest. The formula I will use is:

$$A = \frac{\vec{w} \cdot \vec{d}}{|\vec{w}| * |\vec{d}|} * |\vec{w}| = \frac{\vec{w} \cdot \vec{d}}{|\vec{d}|} \tag{5.2}$$

The second smaller relationship is the combustibility. For the scope of this IS project, combustibility will simply be a user choice value between 0 and 1, rather than a true formula or calculation. It represents how combustible the patch is, merely based on the characteristics of the patch. With more experience and research, combustibility could be developed into a function of base fuel type, drought levels, temperature, and other forest factors.

Using the two relationships above, L can be defined as

$$L(c, \vec{d}, \vec{w}) = \alpha A + \beta c - \gamma d - \lambda \tag{5.3}$$

where d is the absolute distance a patch is from the ignition point. As the value of

A or the value of c increases, the probability $P(\vec{w}, \vec{d}, c)$ will increase as the overall value of L will become more positive. As the value of d increases, the value of L becomes more negative, so the probability will decrease. The value of λ will ensure that when the values of A, c, and d are zero, the probability is close to 0.

To find the parameter values of the equation, I created a set of hypothetical data that follows the pattern that I wanted to be represented in my simulation. I did not factor in the calculations for A during this process, as that simply reduces the scale of the wind so was not necessary. Instead, I used the scalar value of the wind in the direction of the patch, the absolute distance the patch was from the source, and the combustibility. I set up a series of wind values from 0 to 15. Given the domain of wind I used, it is reasonable to only include wind values for which the maximum strength of the wind is less than 15 units per tick. I set up the data so that if the wind is higher than the distance, the probability is the value of the combustibility. If the wind is less than the distance, then the probability is zero. I made the data for a range of combustibility values for 0 to 1, and a range of distances from 1 to 14. It did not make much sense to talk about distances of 0 in my hypothetical data set, as I will never be asking a patch to send a spark to itself, since it is already lit. Within the scope of my net logo model, I only ask patches within 5 units of the origin due to the computational ability of my computer. Using that data, I made a linear regression equation predicting the L value of burning given a specific wind factor and distance. The resulting regression equation, found by using R, has the following summary:

From this equation, I created a mathematical approach to the fire spread within my net logo model, plugging in values for wind speed and and a combustibility value. Using that value for L, I have a complete probability model for predicting if

Variable	Estimate	Error	P value
Intercept	- 9.244	0.459	$< 2e^{-16}$
Wind	0.542	0.0395	$< 2e^{-16}$
Distance	-0.738	0.0495	$< 2e^{-16}$
Combustibility	11.036	0.568	$< 2e^{-16}$

Table 5.2: Linear Regression Model of Dummy Data

a patch is going to light based on probability. The complete equation is:

$$P(c, \vec{d}, \vec{w}) = \frac{1}{1 + e^{-(0.542(A) + 11.036(c) - 0.738(d) - 9.244)}} \tag{5.4}$$

CHAPTER 6

Final Net Logo Model

The structure of the fire model is not super complicated. It has global variable and structural definitions followed by four functions that are used to define the function behaviour: Setup, Go, Ignite, Fade Embers.

The global variables used in this simulation are variables that do not appear in the user interface, however they are useful in keeping track of information or defining the model. The global variables are initial trees (initial-trees), burned trees (burned-trees), the total embers created (Embers-created), and the total number of fires created (fires-created). The total fires and the total embers will be similar numbers, as all fires turn into embers. Other variables used in the equation are the x value of the wind (wind$x$), the y value of the wind (wind$y$), and the combustibility factor (c), all three of which are obtained buy the user interface of the model, which can be seen in appendix figure A.1.

The next structural element of the simulation is the definition of the different turtle breeds. This simulation has both fire and ember breeds. On their own, they don't have many characteristics, which in part is due to the minimal job they have in the simulation. The one characteristic the turtles do have is a tick-time variable, which represents the amount of burn time left in a fire. Both the fire turtles and the ember turtles have access to the tick-time variable, however only the fire turtles use it for anything.

6.1 Set Up

The set up function both sets up the simulation environment and initializes fires created, total fires, and total embers to zero. To create the environment, it clears the simulation of any patch information. It then sets up the environment so that the turtle shape is square, and the simulation has a set density of green patches. To do this, it has a function that randomly selects a certain percentage of the patches in the simulation, and then changes the patch color. The next step in the set up function is to create the initial ember, which is located at the very center of the simulation. It breeds a new fire on that location. Once the fire has been created, it initializes all the global variables, setting initial trees equal to the number of green patches at the start, and setting total fire, total embers, and burned trees equal to zero. It does not count the first fire point as a bred fire, as it will ignite in all conditions with no chance of not igniting.

6.2 Go

Once the setup function is done, the simulation can actually run. To do that, the Net Logo simulation calls the go function. The first part of the go function is a check to make sure the fire is not extinct and faded away. If it is, the simulation is told to stop running, and for the purpose of data collecting, to export all the data information into a CSV document. On the user interface side, there is also have an increment counter so that multiple simulations can run continuously without overwriting the data from the previous simulation. The user has the ability to reset the counter by using a slider.

If there is an active fire or ember, it continues running the program. The next step is to run the ignition probability function, in which each fire has the ability to ask the neighboring patches to ignite. To include the probability model I found above, I created and implemented a double foreach loop in Net Logo. The first loop traverses the x coordinates from -5 to 5. The next loop traverses the y coordinates from -5 to 5. By traversing the loop, it allows for each fire to ask each of the 99 patches around it to potentially ignite. Once the two coordinates are obtained, the Pythagorean formula is used to calculate the absolute distance of the patch. In addition, the value of A is found by using the vectors of the wind and the location. The next step is to have all the active fires use the probability function to determine if they successfully create a spark which ignites a neighboring patch or not. To find that value, an if statement is implemented where if the random float from 0 to 1 is less than the probability of ignition, the patch is asked to ignite. The flaws in this system is that a fire can ask each of the 99 patches around it to ignite, so could in theory, have an almost infinite number of sparks. In a more real life scenario, one fire may only create 20 - 30 sparks, not 99. This does end up working out, because as soon as a patch is ignited, no other fires can ask it to re-ignite.

Once all the fires have asked all of their neighboring patches to ignite, the fade embers function is called, which will be explained in a following section and is responsible for the fires "dying". Following the fade embers function, the current fires are asked to reduce their burn time remaining by 1, and then all the fires with a remaining time of zero are asked to change their breed to embers. It also increments the total embers count at this section of the code.

At the end of go function, the tick counter is incremented, and the function repeats.

6.3 Ignite

The ignite function is responsible for creating new fire variables once a spark has successfully lit a neighboring patch of forest. To do that, the ignite function breeds a new fire on the patch, and turns the patch color black to represent the fact that it has been lit. The only thing I changed from the base model is to include the burn time variable for each turtle. I want the fires to burn longer than a single tick, which is more representative of a tree burning over a longer period of time. Thus I have the burn time variable initialized to 3, so that it burns for a time of 3 ticks. The ignite function is also responsible for incrementing the total fires count and the total burned trees count, as there is no chance of accidentally igniting the same patch twice.

6.4 Fade-Embers

The final aspect of the code is the "fade-embers" section. As it is primarily an aesthetic aspect of the code, I did not implement any changes to it. It is the function responsible for the turtles fading to blackness after 12 ticks, so it could be altered to change it so that the simulations do not run quite as long after the fires are all embers. To do this, it has the ember turtles slowly reduce their red color, turning each turtle closer to black. The fading transition can be seen in figure 5.4.d, with the embers fading from the fire turtles on the right to the dead patches all the way along the left border. Once it gets too dark, it transitions entirely, with the turtle dying out and the patch being set to the deep maroon seen in the left most column of patches in figure 5.4.d.

While the embers are pretty, they do not contribute to the fire spread or intensity in any way, as the embers do not have the ability to propagate any new fires or re-catch fire. The only impact they have is shifting run time. If it takes the embers 12 ticks to fade, then each run has a minimum run time of 15 ticks (3 for the fires, 12 for the embers). If they decrease faster, then the simulation may have a minimum run time of only 6. Thus, their effect would be interpreted as the total run time of a simulation rather than the shape or intensity of the simulation.

6.5 Using the Program

To actually run the simulation, the user has a few steps to do. The first is the set up. The user has a slider they can use to select the forest density, which ranges from 0 to 99%. Once it is selected, they can click the set up button, which will create the forest landscape. From there, the user can enter the combustibility rating, and the x and y wind values. Once all the variables are set, the user hits run and can watch the fire spread. At the end of the run, the program comes to an end, and the process can be repeated. There is an option to have a continuous update to see each part of the fire simulation, or just see the final conclusion.

CHAPTER 7

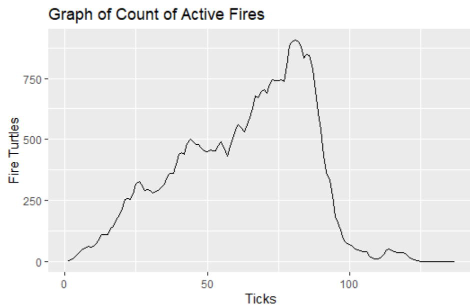
Results

To actually address the impact each of the different variables listed in section 5, I ran a series of simulations under different conditions and collected the results. I created a baseline simulation, and then altered the variables independently to see how the fire shape, spread, and size responded.

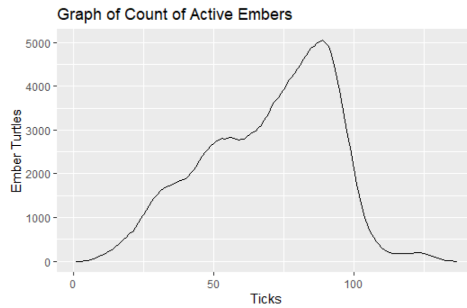
7.1 Methods

There are a few factors that I kept the same between each run to help make the data more generalized. For each run, the density of the forest is 75%, and the seed is set so that the forest is identical for each of the different trials that are run. By holding this constant, the data collected is only related to the fire burn probabilities and structure, and thus are easier to compare. The factors that I will be changing, one at a time, are the combustibility, and the wind. I will only be talking about a few different trial situations in this section, where I address each of the variables individually. I will be examining increasing or decreasing combustibility while holding wind steady, and increasing or decreasing wind while holding combustibility steady. Once I have looked at the effects of each of the variables on their own, I will also be running simulations at small increments from the baseline to determine what level of difference is needed to create statistically different results.

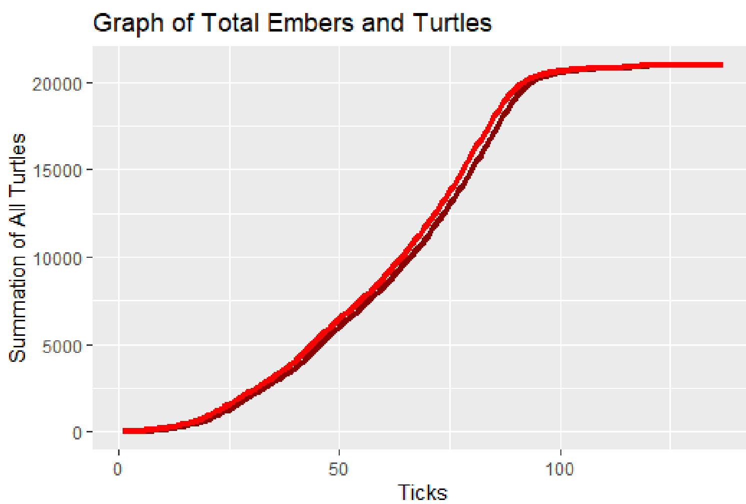
For each trial, I collected 4 sources of intentional data, meaning graphed and



(a) Current Turtles



(b) Current Embers



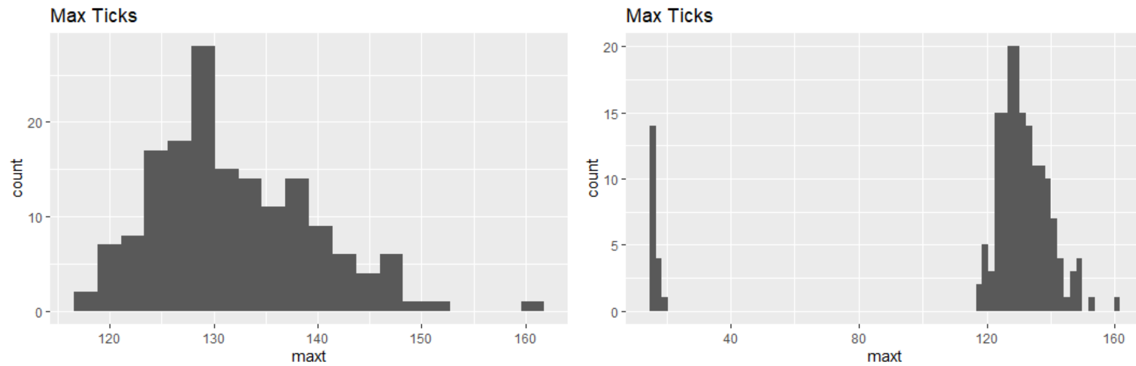
(c) Summation of Fires and Embers

Figure 7.1: Graphs of Collected Data

defined data, and one source of unintentional data meaning there is not necessarily a graph for it, but I can use it. For each trial run I collected the number of active fires at each tick, the number of active embers at each tick, the total summation of all fires throughout the run, and the total summation of all embers throughout each run. The total embers and total fires should end up as the same value by the end of the run, as each fire turns into an ember, however the graph is a little more rapid for the fires than the embers. A graph of the two from one of the baseline values is given in figure 7.1.c. The brighter red line corresponds to the summation of fire turtles, since they are colored bright red in the simulation. The darker red line just barely to the right of the fires line is the embers line. They mirror each other, with a three tick delay between the fire line and the ember line. The shape of figure 7.1.a, which is the current fires graph, is the most jagged, as the specific number of fires at each tick of the simulation has a decent level of variability. In general, it follows a positive trend until the point at which the simulation fire line first reaches the edge of the simulation space, and thus runs out of available patches, at which point it decreases rather rapidly. The end tail of the graph continues, and represents any additional burning along the edges of the simulation, or back burning of new patches. The graph in figure 7.1.b resembles a smoother version of the fires graph, as the variability in the fires at each tick is smoothed out over time, and thus the change is embers is not as dramatic.

The one source of unintentional data I collected is how fast the fire terminated, which is represented by total ticks. Each fire can terminate one of two ways. The first is to reach the border of the simulation, in which case the fire has no more neighbors to ask to burn, and will die out due to lack of resources. This is roughly similar to a containment line, which can either be "natural" like a road or a water source, or created, such as by cutting down resources for the sole purpose of creating a fire containment line. The second is the probability is too low to continue burning. Most fires that effectively start and spread will terminate due to reaching the border of the simulation rather than naturally burning out due to the evenness of distribution of the trees across the entire simulation.

Once the information to be collected was defined, the situations in which data would be collected from needed to be defined. The first set of results I captured were the "normal" circumstances. Given that the formula has no actual real world data beyond trends, there is no real world paramaterization for the baseline variables. Thus I have chosen to go with a baseline value of 0.5 for the combustibility, and 4 units per tick of wind in both the positive x and positive y directions. At this level, the fire looks like it has a decent spread rate, without being too thick, or too thin of



(a) Successful Burns **(b)** All Burns

Figure 7.2: Distribution of Maximum Ticks

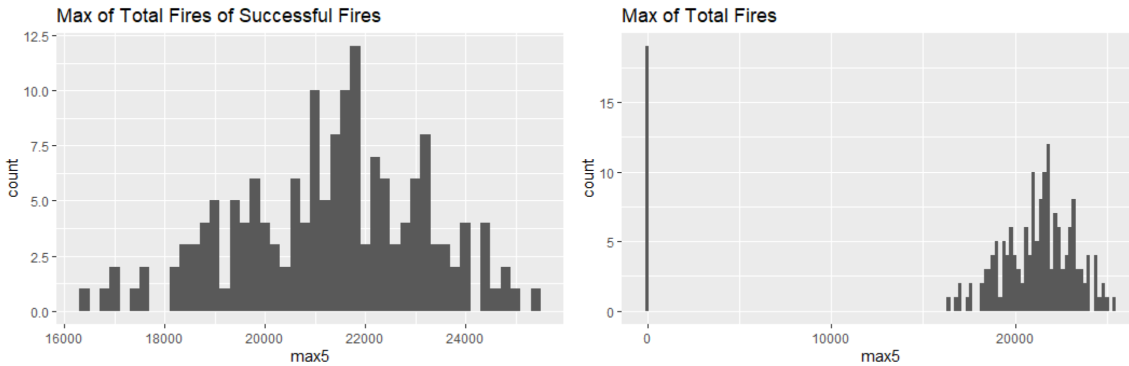
a fire. In addition, these values allow for increasing values to not be too difficult on my computer.

7.2 Data

I ran a total of 181 simulations at these baseline values. At those levels, the fire simulation had a successful burn, where successful is defined by reaching the edge of the simulation, 90% of the time. Of the 10% that didn't reach the edge, they failed to light entirely, not producing a new ember outside of the initial ignition point. The distribution of total ticks, and total fires are seen in figure 7.2. and figure 7.3 respectively.

Additional graphs for other variables are included in the appendix.

As seen from these graphs, there is a clear separation between the 18 simulations that did not have a successful ignition, and the rest of the simulations. The distribution among the rest of the simulations appears roughly normal. There is a distinctly different scale for the different metrics measured. Figure 7.3, graph a, which represents the total active fires, has a maximum of 1069. Eliminating all of the unsuccessful burns, which is seen in graph b, the minimum increases to 750.



(a) Successful Burns

(b) All Burns

Figure 7.3: Baseline Fire distribution of successful burns

The maximum for total active embers is 5757 and the maximum for total fires or embers of the entire simulation is 25,404 and 25,405 respectively. The one turtle difference is due to the set up of the simulation. Since the initial spark is created before the count variable is initialized, it is not included in the total fire count. Since it does not represent the fire spread, I have chosen to leave this order untouched. The longest simulation was 160 ticks. The distribution of the 5 metrics are given in table 7.1. Since the unsuccessful fires, or those that did not ignite beyond the first spark, skew the mean and standard deviation, I have broken up the distribution of statistics into all the runs, categorized by the "t," and only those runs which successfully spread from the initial point, categorized by the "s."

Given the baseline distribution from the 181 total runs and just the runs that had a successful ignition, the values can be compared to those of other conditions. To look at each of the variables independently, I conducted 10 runs at the variations, and compared their runs to the distribution of the baseline values.

The first variation from the normal conditions I studied was reducing the combustibility. Reducing the combustibility from a value of 0.5 to 0.3 gave vastly different results from the "baseline". Reducing the combustibility to 0.3 resulted in none of the 10 runs ignited to a successful burn, all dying out from the first fire.

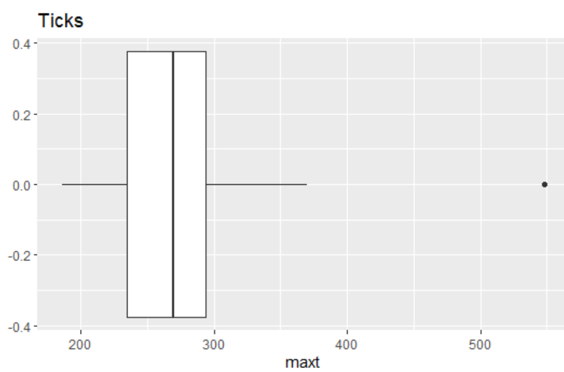
Variable	Min	Q1	Med	Q3	Max	Mean	SD
Total Ticks (t)	15	125	130	136	160	119.7	36.57
Total Ticks (s)	117	127	131	137	160	131.89	7.54
Active Fires (t)	1	815	883	935	1069	801.4	284.4
Active Fires (s)	672	835	903	943.75	1069	895.27	77.94
Active Embers (t)	1	4491	4886	5214	5757	4418.67	1564.25
Active Embers (s)	3872	4643.5	4936.5	5254.5	5757	4936.67	404.45
Total Embers (t)	1	19391	21235	22431	25405	19059	6779.02
Total Embers (s)	16463	19951.25	21463	22646	25405	21294.15	1868.96
Total Fires (t)	0	19390	21234	22430	25404	19058.06	6779.02
Total Fires (s)	16462	19950.25	21462	22645	25404	21293.15	1868.96

Table 7.1: Distribution of Maximum of Baseline Values

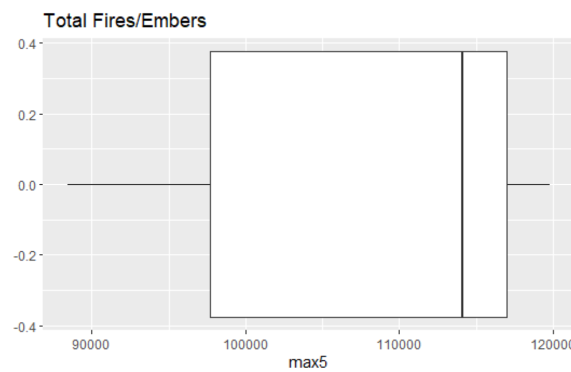
The complement to reducing the combustibility is increasing the combustibility. I chose to increase by 0.2 as well, running the simulation with a combustibility of 0.7. The box plots of the distribution of the 5 metrics, with total fires and total embers on the same graph, for the 10 simulations are given in figure 7.4

From the graphs, we can see a dramatically different scale for the maximum counts. The maximum number of ticks for any of the 10 runs is 548, compared to 160 for the baseline. This difference shows that the fires burn longer than the baseline values, despite reaching the border of the simulation at an earlier tick. Most likely this is from an increased probability of burning in directions other than the main wind direction, as seen in the visual of the completed simulation. The minimum run time for any of the 0.7 combustibility fires is 186. All of the 5 variables had a minimum value greater than the baseline's maximum value.

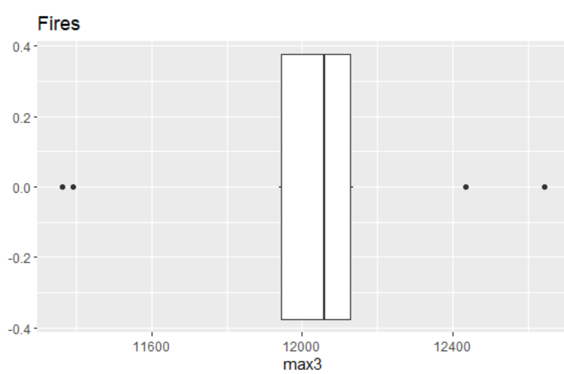
The next step was to see the effect of increasing or decreasing the amount of wind when holding the combustibility factor level. Decreasing the wind yields similar results to decreasing the combustibility. The longest run time was 10 ticks, with almost no additional fires created after the ignition point. Even though each patch of tree has a rating of 0.5 to ignite, the ability for the fires to create sparks



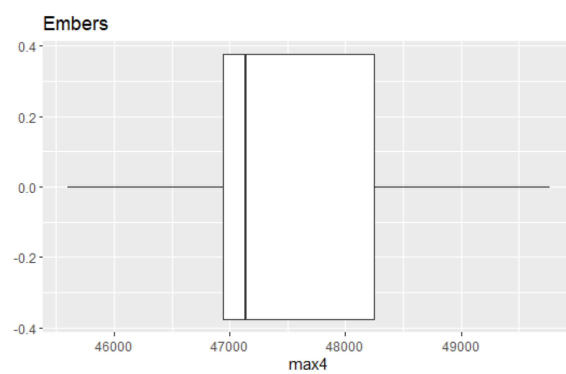
(a) Ticks



(b) Total Fires/Embers

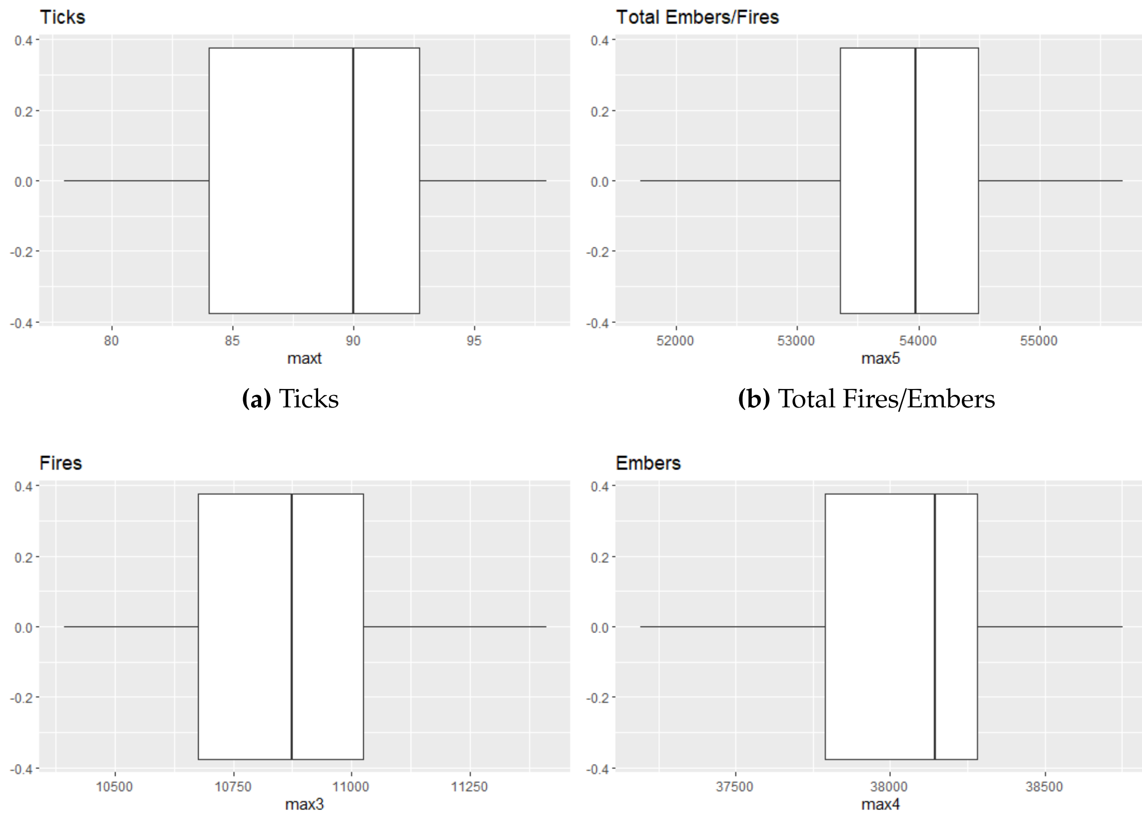


(c) Active Fires



(d) Active Embers

Figure 7.4: Distribution of High Combustibility Graphs



(a) Ticks **(b)** Total Fires/Embers

(c) Active Fires **(d)** Active Embers

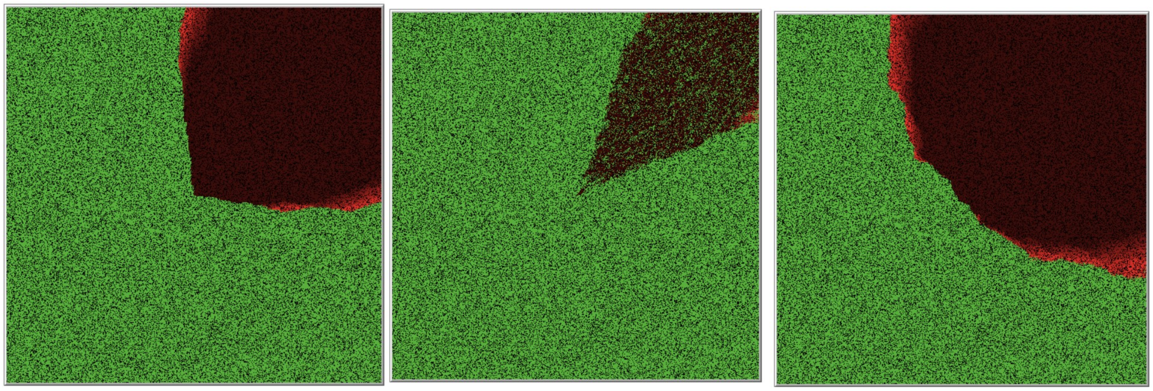
Figure 7.5: Distribution of High Wind Graphs

that successfully travel to the neighboring patches is reduced enough to essentially prevent fire spread.

Increasing the wind to double, at a value of 8 units per tick in both the x and the y direction yields results similar to increasing the combustibility, in which the fire grows much larger than the baseline fire. However, the method in which it spreads is very different.

7.3 Discussion

While these simulations are not grounded in actual data, the trends they show are still applicable. The most notable to talk about are the change in the way a



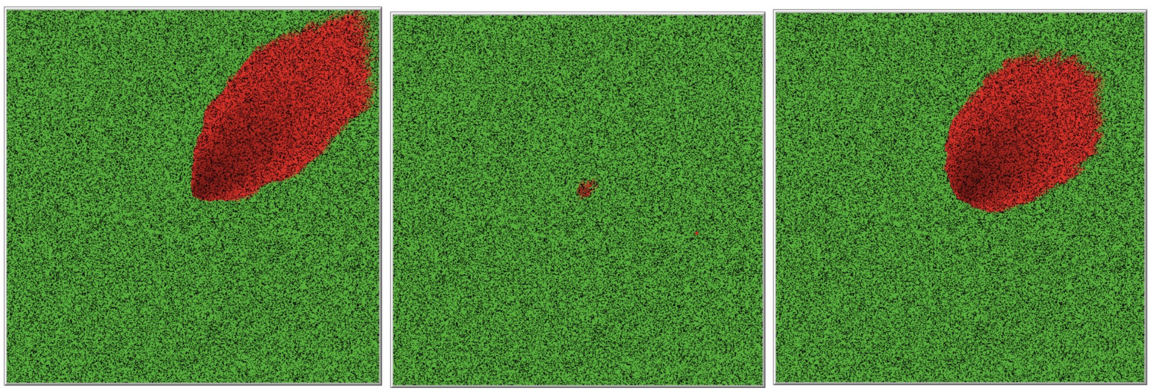
(a) Higher Wind **(b)** Baseline **(c)** Higher Combustibility

Figure 7.6: Simulations at near completion

fire burns when increasing combustibility compared to when increasing the wind. Both increasing the amount of wind and increasing the combustibility increases the severity of the burn, as seen by the increase in active fires and total fires in figures 7.5 and 7.4 compared to the baseline distribution in figure 7.3. However the way in which they increase in severity are different. Increasing the combustibility resulted in a much higher number of fires and embers throughout the simulation. The baseline had a maximum active fire range for successful fires of 672 to 1069. Increased wind had a maximum active fire range of 10392 to 11412, and increased combustibility had a range of 11362 to 12643. Both have significantly more active fires than the baseline model did, which means the number of sparks throughout the fire are much higher. In a real life setting, this would mean more chances for the fire to jump a fire line, move unpredictably, and make the fire harder to fight in general, which matches up with the prior understanding of fire risks. In addition, the fire spread farther from the expected fire burn area found in the baseline simulations.

Comparing the images in figure 7.6, the baseline fire simulation moves in the direction of the wind, which is a positive x = y direction. The higher wind spreads farther out from the wind direction, creating a 90 degree structure of the burn section of forest, leaving no live trees in the burnt area. The high combustibility fire covers a much larger section than the other two simulations, branching out in directions farther from the direction of the wind. In terms of predictability, the higher combustibility would be considered the least predictable of the three simulation conditions as it strays the furthest from the baseline direction.

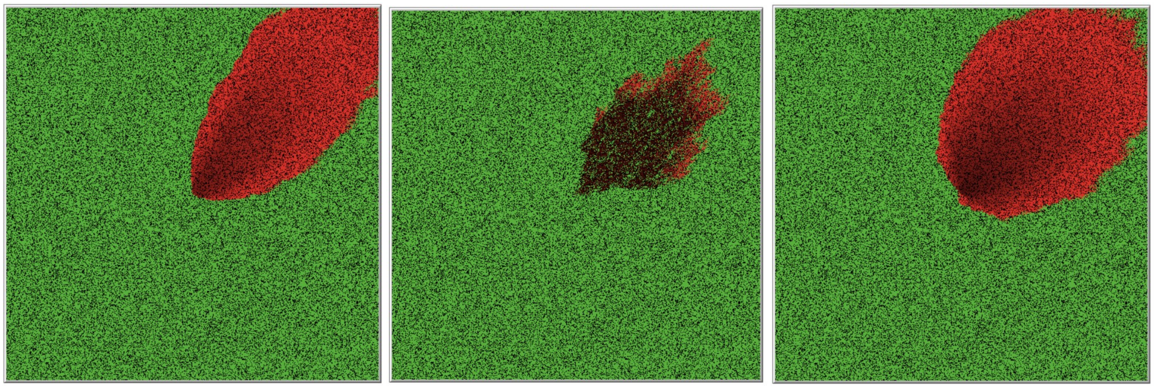
However, there is a second narrative between higher wind and higher combustibility that is important to talk about, and that is the speed at which the fire spreads.



(a) Higher Wind **(b)** Baseline **(c)** Higher Combustibility

Figure 7.7: Simulations at 10 ticks in

The difference is that the tick time was much shorter for the simulations with a higher wind spread. The spread of the baseline tick time is 117 to 160. The spread of the increased combustibility is 186 to 548, and the spread for increased wind is 78 to 98. We see in figure 7.7 a collection of three different simulations, one with higher wind, one with the baseline values, and one with higher combustibility. All three simulation screen shots are at 10 ticks into a run. The higher wind simulation is almost at the border of the forest, the baseline simulation has just begun burning, and the higher combustibility simulation is in between the two. If given an unlimited forest to burn, the higher wind and higher combustibility would continue to burn indefinitely, so the takeaway from the difference in tick time is more to do with how the fire fills the simulation space than the speed at which the fire dies. The fire with



(a) Higher Wind **(b)** Baseline **(c)** Higher Combustibility

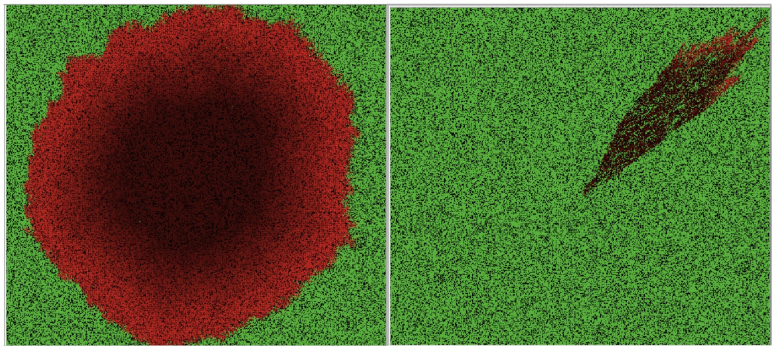
Figure 7.8: Simulation Fire Lines

an increased wind spreads so quickly that it runs out of fuel in front of it to burn, and has low enough combustibility that there isn't a significant amount of back burning. In contrast, in the higher combustibility simulation, the fire reaches the edge of the simulations at roughly the same time as in the higher wind simulations, however it continues to back burn for a longer time, which also contributes to the wider section of forest burnt in figure 7.6.

From comparing the two, neither increased wind nor increased combustibility are good, as they both contribute to a much more dangerous burn condition, which is in line with forest service red flag warnings discussed earlier. Going from that, controlled burns should never be allowed in high wind situations, even at lower combustibility ratings. The fires create too many embers, which spread very quickly. Even though the direction of the fire stays within the direction of the wind, the speed in which it spreads forward makes it very unpredictable and hard to manage. Another important thing to look at for the models with a high wind spread is the depth of the fire line. The baseline model has a clear leading fire edge without too much depth, followed by a section of embers, whereas the other two simulations have a very much thicker fire line, or a more depth in the fire turtles, and the ember trail doesn't begin until after the fire has reached the edge of the simulation. In a real life situation, one can look at the Marshall Fire, which burned through sections of Boulder and Louisville, Colorado in December 2021. The fire burned 6,000 acres within 24 hours, and quickly became the most costly fire in Colorado history [9]. The fire was made so destructive due to the extremely dry conditions and the extremely high winds. Experts estimate the moisture content of the fuel sources was likely less than 10%, caused by the drought seen across the Western United States during the past couple years. Winds on that day reached upward of 100mph, carrying the fire at a rate of over 60mph for the front fire line. Due to the dry fuel and fast moving nature, containment efforts such as laying down fire retardant, removing fuel sources, or creating other natural barriers, were difficult to utilize, as it was moving too fast to be predicted. Some neighborhoods were left obliterated, while others showed minimal signs of impact from the fire.

Both trends are important to talk about, as both are very relevant and important to consider when addressing if a fire management approach should be focused on suppression efforts or merely containment efforts. If the conditions during the day are too extreme for either variable, it is best to focus on suppression efforts, which work to decrease the combustibility of patches of forest. There is no way to say which condition, wind or combustibility, is inherently worse, as they work together to create fire spread. Lowering wind conditions allows for a forest to have a higher combustibility rating while still having “predictable” conditions, and lowering the combustibility allows for controlled burns in higher wind speeds.

Simulations in which there is no wind, yet there is a really high combustibility rating burn outwards from the center patch, and do result in a burn that reaches the edge of the simulation space. An example of this simulation can be seen in figure 7.9. Thus, as current trends of forest weakening, increased drought, and more extreme temperatures continue, a discussion of wind becomes less relevant, because



(a) High Combustibility **(b)** High Wind

Figure 7.9: Simulations at extreme wind or extreme combustibility

the forest is simply too combustible, and will ignite regardless. The wind will only work to make the fire even more dangerous in a specific direction.

In contrast, a really high wind speed with no combustibility does have a burn line which reaches the edge of the simulation space, simply due to the amount of embers that are moving in the direction of the wind. There is some slight deviation from the specific direction of the wind, however not a lot. Burning in situations with high wind could be useful in creating fire lines for future fires, as it creates a small burned section. However, as seen in figure 7.9.b, there are green patches left within the fire line that would still be valid to burn for future fires.

However, a lack of both wind speed or combustibility will result in no fire spread. Right now winter conditions better mimic this, where the increase snow and decreased temperature reduce the combustibility of the forest. Controlled burns would be minimally, if at all, effective at being a better forest management practice, as the fire resources needed to successfully create a controlled burn would be more costly than the results themselves. This is seen in the fact that none of the simulations with a decreased combustibility or decreased wind ever resulted in a successful ignition.

Changing the baseline to different conditions would make the impact of a 200% change in wind very different. The baseline that I chose allowed for extreme differences in fire to isolate each of the conditions. To get a statistically significant difference in the metrics, the fire combustibility only needs to increase to around 0.53, or decrease to 0.48, and the wind needs to change by around 1 unit per tick in both the x and the y. The simulation is very sensitive to small changes, and thus extremely sensitive to the large changes that I implemented in my 4 experimental conditions.

The bigger take away from these simulations is the importance of decreasing the combustibility of our forests. Humanity has yet to establish a way to reduce the wind, so that is a factor that is always going to be relevant. Thus, efforts should and need to be focused on doing actions that help our forests. Those can include allowing prescribed burns to thin out forests, encouraging lumber efforts to clean out dead or dying trees, actively working to reduce global emissions which will in turn help reduce temperatures and increase moisture.

CHAPTER 8

Weaknesses

The simulation still has a lot of weakness that could later be addressed and corrected to create a better simulation. The first, and most evident weakness, is the lack of real world applicability that the project has. Since there is no real world data representing the wind and distance relationship, or the combustibility, the values are entirely hypothetical based on a pattern that seemed appropriate. While the trends are worthy of a conversation, the degree to which they play a role are entirely hypothetical. However, this could be remedied fairly easily by including the usage of real world data to create a probability equation such as the one seen in equation 5.4. While the structure may change, the implementation of the equation into the simulation space would be the same.

Building off the issue of the lack of real world values, the equation is also extremely simplified in terms of the combustibility rating. In practice, a combustibility rating would be determined by factoring in temperature, humidity, fuel type, age of the fuel, how alive or dead it is, how long it has been since the last rain fall, what side of a mountain it is on and so much more. An actual equation could be determined, but collecting all the factors that contribute to a combustibility rating would likely be expensive and difficult to do. Instead, generalizations could be made that would group sections of forests into similar combustibility ratings, yet it would still be more complex that the one included in this model.

In line with the simplicity of the model is the sensitivity of the model. From the baseline simulation, changing the combustibility by less than 0.05 creates statistically different results, meaning that 10 out of 10 runs at a combustibility of 0.55 have more embers than any of the 181 baseline simulations do. Similarly, changing the wind by 1 also yields the same results. The sensitivity of the baseline simulation to these minor adjustments may be exaggerating the difference the wind or combustibility can have. From that, taking away the conclusion of increasing combustibility creates a “dramatically different” simulation may not be the most accurate. Instead, trends relating an increased combustibility to an increased wind are more important to look at the than the numbers themselves.

Beyond that, there are still a couple assumptions discussed in 5 that were not addressed in my simulation modifications that should be addressed in further research. I already addressed the potential to create different colored patches to better represent different forest characteristics, such as blue patches for more grassy sections, green patches for more tree sections, and brown patches for bare sections. This ties well into the assumption of equal burning rates in terms of fire life cycle in the simulation. This could either be included as a random variable distribution for life cycle, or just be based on the patch characteristics.

Other assumptions that were not discussed earlier have more to do with the geographical structure of the simulation. The simulation plane represents a flat expanse of forest with uniformly random distribution of trees at a certain density. In reality, forests are a lot more structured than that, with more trees forming along water sources, and patches of forest with considerable less trees than other patches. In addition, especially in Western Colorado, forest are not flat. The very mountainous terrain creates unique fire burning situations. It is well known that fires burn much easier up hill. This is due to two factors: the first is that heat travels up, so the up hill section of forests will dry out before the fire line gets there, increasing the combustibility factor of the forests ahead of the fire line [55]. This is part of why the Grizzly Creek Fire in Glenwood Canyon, Colorado burned so fast up the sides of the cliffs. According to the Southern Australia County Fire Services, a bush fire on a hill at 20 degrees will travel up hill 4 times faster than the fire will travel down the hill [5]. Paired with the topological structure on its own, the layout of the land also effects the wind spread patterns. Typically, wind moves uphill as well, further pushing fires faster in that direction. The one factor geography has towards supporting a downhill fire is the ability for fuels to move. In a flat environment, a burned tree branch will stay on the forest floor underneath where the tree was burned. However, on an incline, the burned tree branch has the potential to roll down the hill, spreading sparks farther away or against the wind that could cause a back burn behind the fire line to ignite [40]. While actually including a 3D element to a net logo structure would pose more difficulties, the effects can be simulated by altering the distance and wind speed relationship based on if the patch is representative of "above" the location of the fire.

CHAPTER 9

Conclusion

The forests of the United States provides beautiful scenery across the nation. They are home to many different plant and animal species, providing a source of biodiversity that draws tourists from across the world. In addition to the visual splendor of the forests, they play a vital role in supporting the United States economically. It provides timber, which is used for housing and construction, as well as providing much of the water supply used for farming, drinking, or other purposes. When the United States Forest Service was created, the motivating factor to protect our forests came out of an economic interest to protect the timber. In line with that goal, the United States embarked on an aggressive forest fire elimination policy, in which all fires were to be eliminated as quickly as possible, and future fires should be avoided at all efforts.

However, instead of protecting the forests and the timber within them, this aggressive approach led to an increase in ground fuel within the forest, a weakened forest system overall, and a much denser forest altogether. Further research proved that the approach had not created a better timber supply, but instead left our forest in a delicate state. With the turn of the century came a new approach to managing forests, in which the health of the forest became a concern rather than just the economic promise of additional timber. Efforts became safe containment of fires rather than complete suppression, and an effort to allow our forest to self regulate through prescribed and controlled burns. In addition, wildfires that were deemed safe enough were allowed to free burn to extinction as well. But the turn came too late, and the forests are already at an irreversible weakened state.

With the weakened state of the forest, wildfires have increased in quantity and severity over the past two decades. Further helping the increase is the change in the environment. The country is seeing widespread drought, increased temperatures, and more extreme wind conditions than in the previous century. The forest and environment paired together have allowed the wildfires to burn more aggressively. The increase in ground fuels increases the total fuel the fires have to burn. The decrease in health of the trees cause the trees to burn more easily as well. The increased density of the forest, while beneficial to increase overall timber production, has allowed the fires to spread easier with less effort, as the fuel sources are closer together. The result of the more extreme fires is more damage to the soil once the fire is gone, which leads to an increased likely hood of post fire rehabilitation. Often the soil results in a burn scar, which can lead to flash floods, and longer recovery time. The higher intensity, paired with the higher frequency, has caused the annual costs of fires in the United States each year to continue to increase. While wildfire reports are often associated with the direct costs of the suppression efforts, there are more factors associated than just those. The Burn Area Emergency Response program helps provide funding for post burn rehabilitation, yet even that is still only a small fraction of the costs of a fire. Often, the economic and long term impact the fires have on the community go unaccounted for.

One potential solution is to ignite controlled burns during periods in time in which the fires are less likely to be as detrimental to the surrounding environment. Those can either be in times of the year in which there are lower temperatures, higher moisture in the fuel, or minimal wind, preferably times in which there is a combination of the three. However, if the conditions get too far in the cold extreme, the amount of human resources and energy used to try to start a preventative burn far outweigh the potential benefit of the burn, as there isn't enough fuel available to actually effectively clear out the forest. When the conditions get too far away from the high humidity, low wind conditions ideal for controlled burn, implementing a controlled burn can be very dangerous. If the conditions are too dry, or the wind too high, the fire has the ability to spread too fast or too unpredictably, which could lead to an uncontrolled wildfire with devastating consequences.

To study the effects increasing wind or increasing the combustibility has on the shape of a fire, I explored using agent based modeling in Net Logo. Agent based modeling allows for the structure of the simulation to be shaped by the interaction of the fires and sparks within the forest to build the shape and spread of the fire. I built a probabilistic equation for the fire spread to put into the model, which takes into account the wind speed and direction, the distance a spark has to travel, and the combustibility of a patch of forest. I ran a series of simulations at a baseline value, and then altered the parameters to see how they individually affect the simulation. While neither the equation or the paramaterization of the variables were founded in real life data, the conclusions are still applicable to trends seen in wildfires across the country. The findings from running the simulations are that high wind and high combustibility both create more expansive fires, however in different ways. Having high wind causes the fire to spread quicker, but to stay roughly 90 degrees from the fire origin point. High combustibility burns slower, however it burns in directions farther from the direction of the wind. Both conditions caused the fire to burn with more sparks and active fire turtles than the baseline did, which resulted in a thicker burn which would likely be much harder to put out than the baseline fire would be.

There is no clear solution in how to reduce or solve the current wildfire problem. Every possible solution comes with its own benefits and cost. One of the best known solutions to date is participating in proactive or controlled burning. The primary reason is due to the large scale effect it can have without needing a significant number of personnel or resources, so long as the conditions are optimal. Other methods of forest management can be less dangerous, however often require extensive personnel efforts, or significantly more resources. By researching how to increase the amount of time during the year communities can create successful yet safe controlled burns, they can be used more effectively. Communities can target controlled burns to sections of the forest that would pose the biggest threat to the wildlife urban interface, so that when massive fires hit there is already a healthier section of forest between the communities nearby.

Other options include supporting logging efforts that actively remove dying or fallen trees from the forest near at risk communities. These efforts are effective in reducing the combustibility factor of a forest by removing the source and spreading out the trees, however they require a lot more time and personnel than controlled burning does. While better for the communities around it, since there is no way for a logging operation to suddenly spiral out of control in the same way as a fire, the benefits from logging take years to actually implement, and the noise population from the vehicles can cause strains on the community.

Regardless of the methods used to help the United States forests get healthier, there is no debate that some action must be taken. As demonstrated by the simulations, reducing combustibility can reduce the spread of a fire. The United States needs to continue prioritizing the health of the forest, and supporting actions that work to remove fallen, dead fuel from the ground, and strengthen the living trees so they can better resist burning in future fires. Otherwise, the United States will only continue to see more dangerous, more costly, and more deadly fires in years to come.

APPENDIX A

Final NetLogo Fire Model Code

Below is the final code I used to run the model simulations. Much of the structure remains similar to the program created by Uri Wilensky in 1997, which I have since expanded to make more robust and more accurate to actual forest fires. A online version of the original fire model can be found at http://www.netlogoweb.org/launch#http://ccl.northwestern.edu/netlogo/models/models/Sample%20Models/Earth%20Science/Fire.nlogo [57].

```
;; Global variables used in the simulation
globals [
  initial-trees ;; how many trees (green patches) we started with
  burned-trees  ;; how trees have burned so far
  i ;; placeholder variable for x coordinate
  j ;; placeholder variable for y coordinate
  dist ;; euclidean distance from turtle to patch
  windpercent ;; the scaled factor of the wind, determined by equation 5.2
  Embers-created ;; how many total embers are created
  fires-created ;; how many total fires are created
]

breed [fires fire]    ;; bright red turtles -- the leading edge of the fire
```

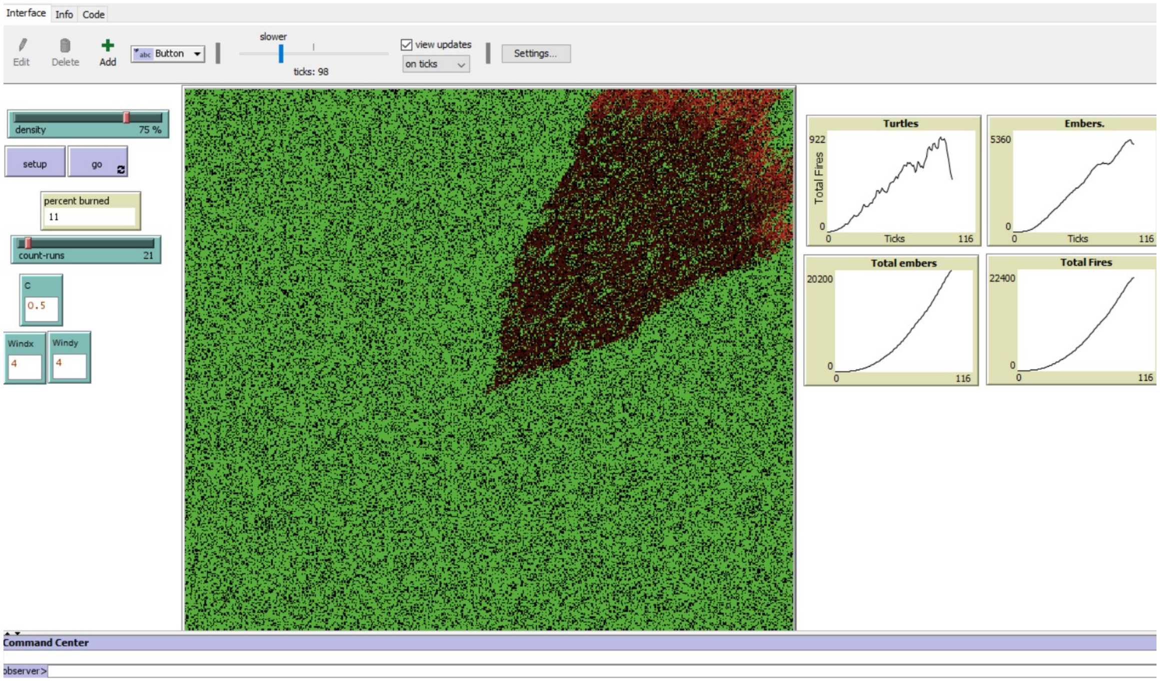
```
breed [embers ember]  ;; turtles gradually fading from red to near black

turtles-own [tick-time]



to setup

  clear-all

  set-default-shape turtles "square"

  random-seed 10 ;; set the seed so the landscape is the same for all simulations

  ask patches with [(random-float 100) < density]

    [ set pcolor green ]

  random-seed new-seed ;; make the seed random again

  ask patches with [pxcor = 0 and pycor = 0]

    [ ignite ] ;; ignite the center patch

  set initial-trees count patches with [pcolor = green]

  set burned-trees 0

  set embers-created 0

  set fires-created 0

  reset-ticks

end



to go

  if not any? turtles  ;; check to see if there are any active turtles

  [ ;; if not, export all infomration

    let cprint c * 100

    let xprint windx * 10

    let yprint windy * 10
```

```
  export-all-plots  (word "Ec" cprint "x" xprint "y" yprint count-runs ".csv")
      ;; export the plots as (example) Ec5x4y412
  set count-runs count-runs + 1
  setup
  go
]


;; loop over the 99 surounding patches
foreach [-5 -4 -3 -2 -1 0 1 2 3 4 5]
[
  x ->  set i x ;; set the x cooridnate from -5 to 5
  foreach [ -5 -4 -3 -2 -1 0 1 2 3 4 5]
  [
    y -> set j y ;; set the y coordinate from -5 to 5
    set dist sqrt(i * i + j * j)
      ;; calculate the euclidian distance of the patch
    if dist != 0
    [
      set windpercent (windx * i + windy * j) / dist
          ;; calculate the value of equation 5.4
      ask fires
      [
        ask patches at-points (list((list i j))) with [pcolor = green]
        [ ;; use the equation from 5.2 to calculate the probability
        of ignition
          if random-float 1 < (1 / (1 + exp(-(-9.244 +
```

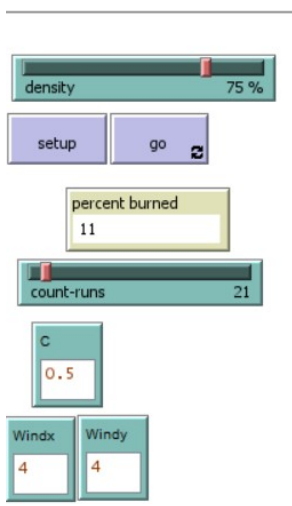
```
              0.542 * (windpercent) - 0.783 * (dist) + 11.036 * (c)))))
          [
            ignite
          ]
        ]
      ]
    ]
  ]
]
fade-embers ;; call the fade embers function
ask fires
[
  set tick-time tick-time - 1 ;; reduce the tick count of each fire
]
ask fires
[
  if tick-time = 0
  [
    set breed embers ;; change the fires into embers
    set embers-created embers-created + 1
  ]
]
tick ;; increment the tick count
end


;; creates the fire turtles
```

```
to ignite
  sprout-fires 1 ;; produce a single new fire
    [ set color red
  set tick-time 3]
  set fires-created fires-created + 1
  set pcolor black
  set burned-trees burned-trees + 1

end

;; achieve fading color effect for the fire as it burns
to fade-embers
  ask embers
    [ set color color - 0.3  ;; make red darker
      if color < red - 3.5     ;; are we almost at black?
        [ set pcolor color
          die ] ]
end
```

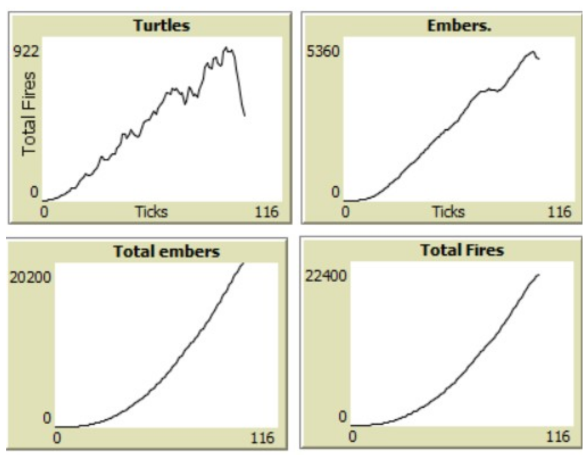
In figure A.1, the boxes on the left hand side are the elements the user can interact with. There is a zoomed in image in sub figure a. From here, the user can input any value for the wind, either positive or negative. In addition, the user can input any value for c. There is no system in place to ensure that the values the user inputs are within the scope of the simulation. It is the responsibility of the user to ensure the wind value is less than 15, and the combustibility is between 0 and 1. The graphs will display the counts in real time for each tick on the right of the simulation space, with a zoomed in look at the graph interface in sub figure c.



(a) Simulation Screenshot



(b) Controls, sliders, and inputs

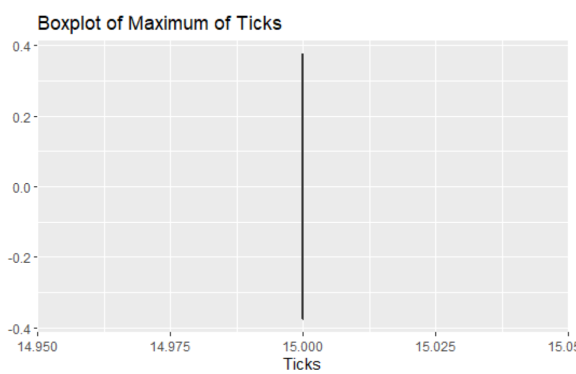


(c) Monitor Graphs

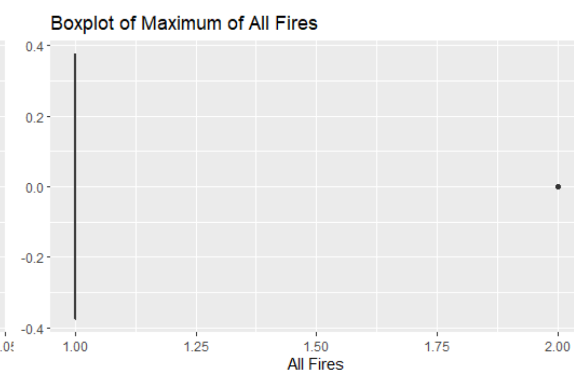
Figure A.1: NetLogo Wildfire Simulation Screenshot: A screen shot of the overall user interface on a windows computer is shown in figure a. A closer look at the user input is in figure b, and a closer look at the monitor graphs is in figure c.

APPENDIX B

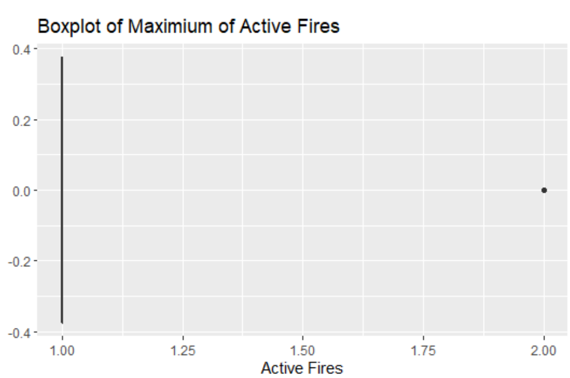
Additional Figures



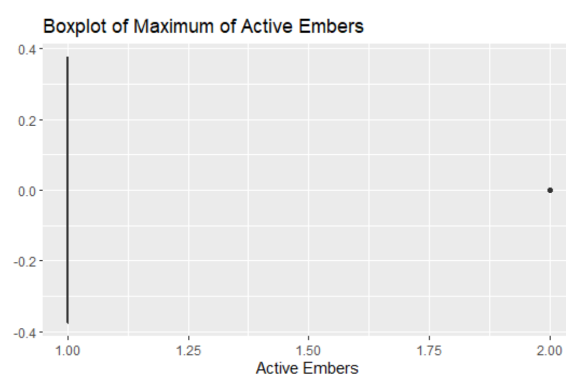
(a) Total Ticks



(b) Total Fires/Embers

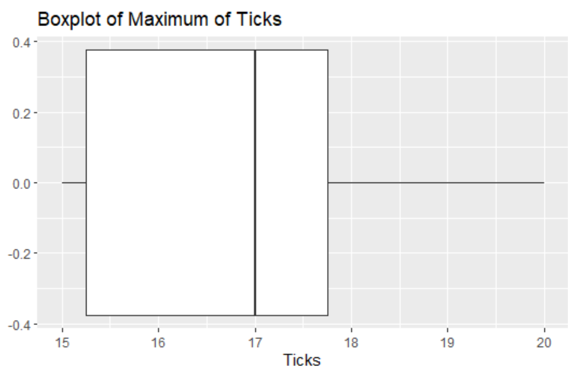


(c) Maximum of Active Fires



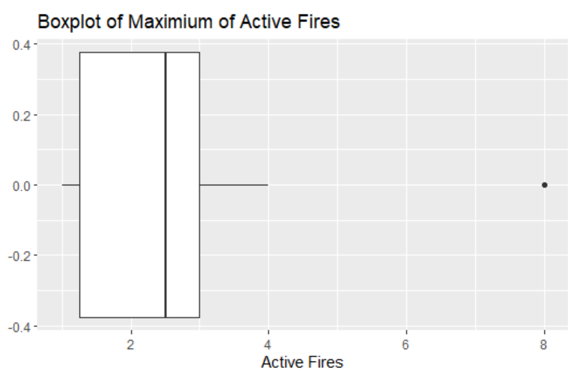
(d) Maximum of Active Embers

Figure B.1: Distribution of Data at Low Combustibility: box plot distribution of the maximums for simulations ran with low combustibility. None of the 10 fires expanded outside the initial ignition point, so the box plots are very boring.

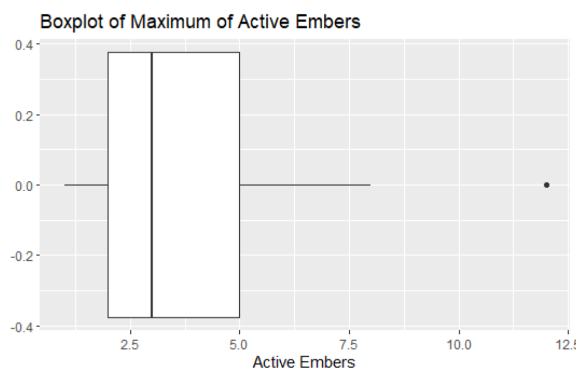


(a) Total Ticks

(b) Total Fires/Embers

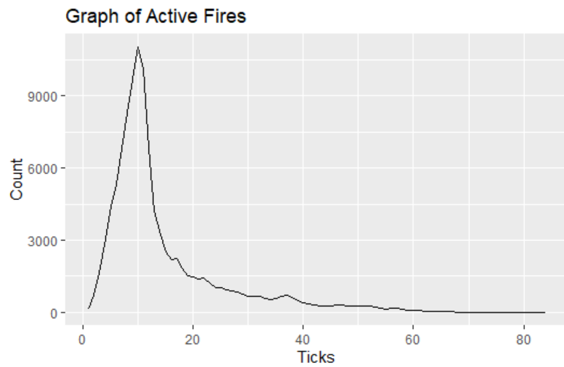


(c) Maximum of Active Fires

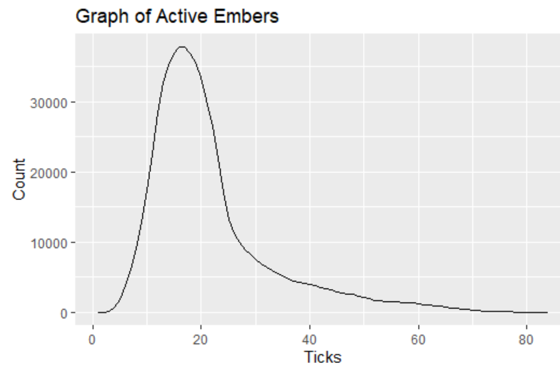


(d) Maximum of Active Embers

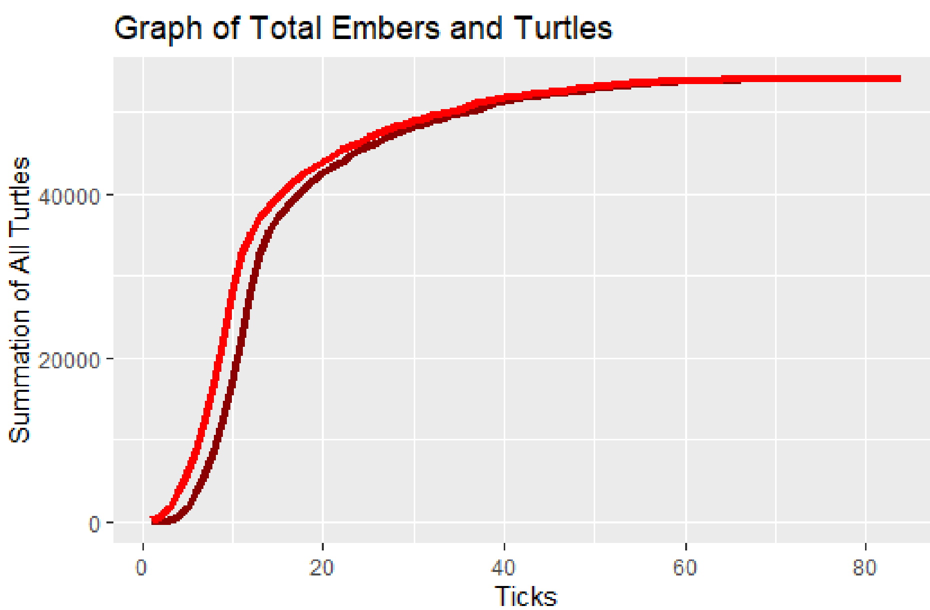
Figure B.2: Distribution of Data at Low Wind: While there was some expansion more than the low combustibility fire simulations, there is still almost no expansion from the initial fire source and immediate neighbors.



(a) Active Fires

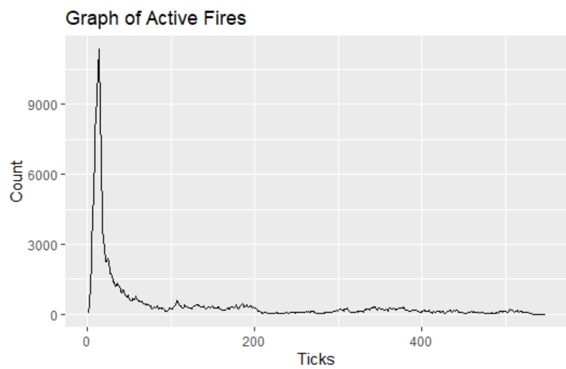


(b) Active Embers

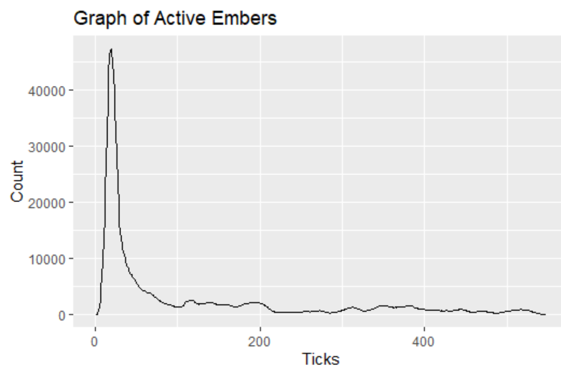


(c) All Fires and Embers

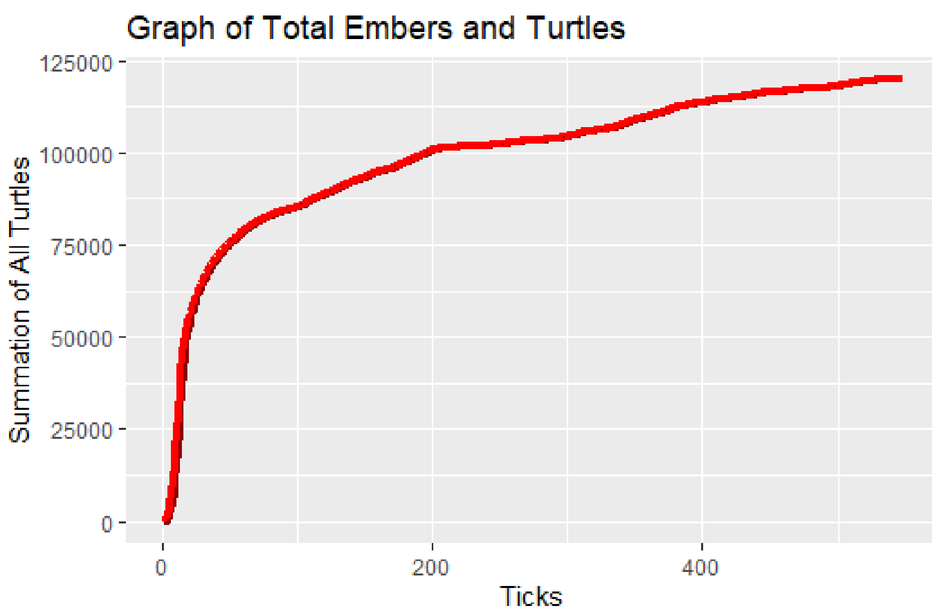
Figure B.3: The figures show the graphs of each of the different values monitored for a simulation with a combustibility of 0.5 and a wind value of 8. Embers and Fires are graphed on the same graph. The space between the total fire and the total ember line is due to the short tick time of the simulations. There is still only a 3 tick difference, just as with other conditions.



(a) Active Fires

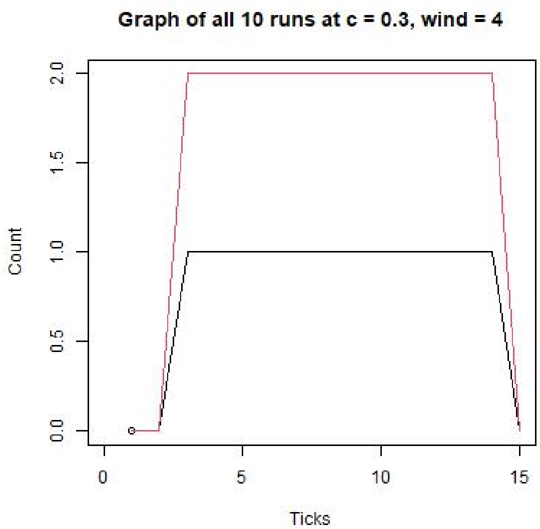


(b) Active Embers

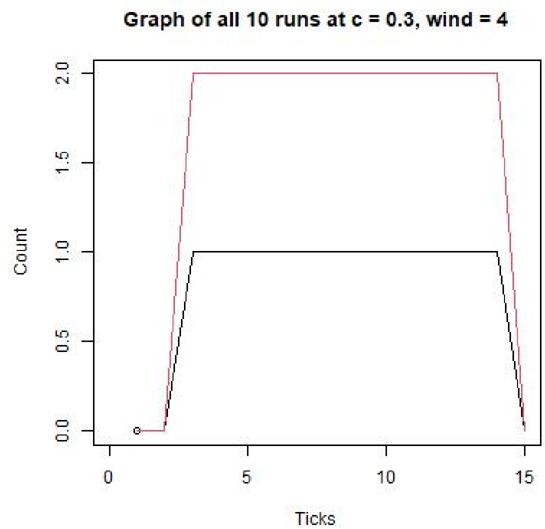


(c) All Fires and Embers

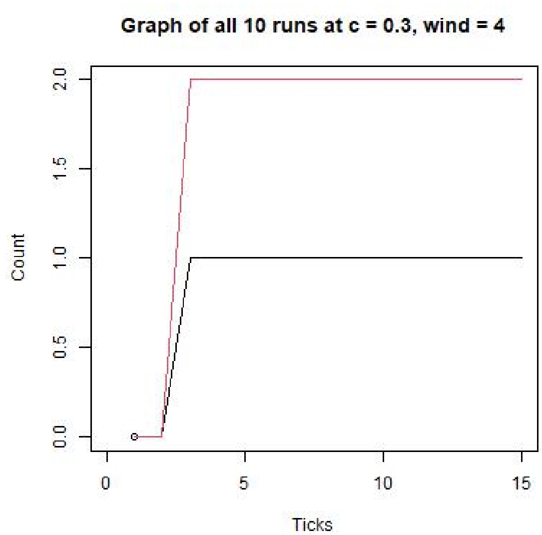
Figure B.4: The figures show the graphs of each of the different values monitored for a simulation with a combustibility of 0.7 and a wind value of 4. Embers and Fires are graphed on the same graph. The lack of space between the total fire and the total ember line is due to the long tick time of the simulations. There is still only a 3 tick difference, just as with other conditions.



(a) Active Fires

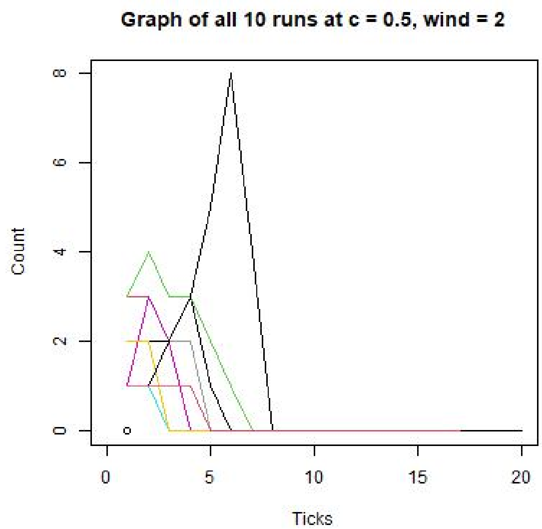


(b) Active Embers

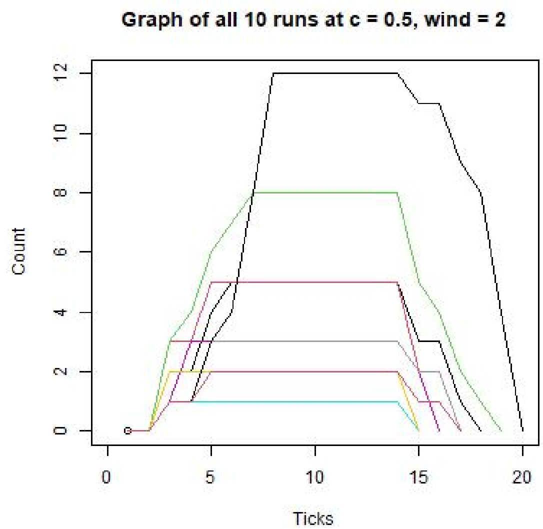


(c) All Fires and Embers

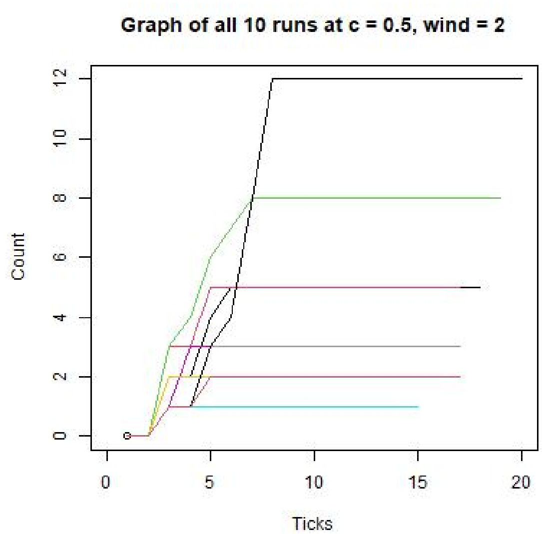
Figure B.5: The graphs show runs at a wind speed of 4 and a combustibility of 0.3. All the runs are different colors. Most of the runs all had just the single ignition point, thus only two lines appear on the graph.



(a) Active Fires

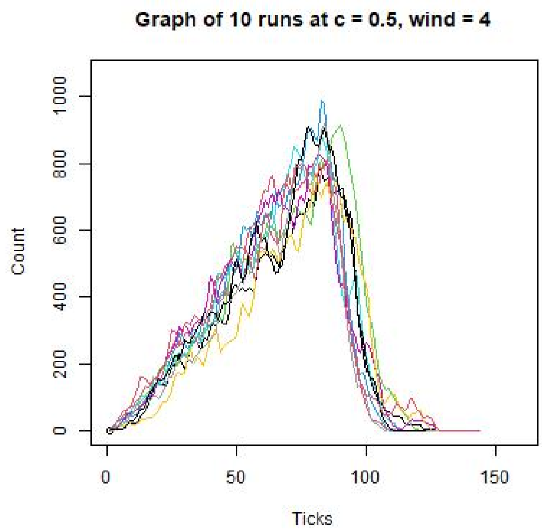


(b) Active Embers

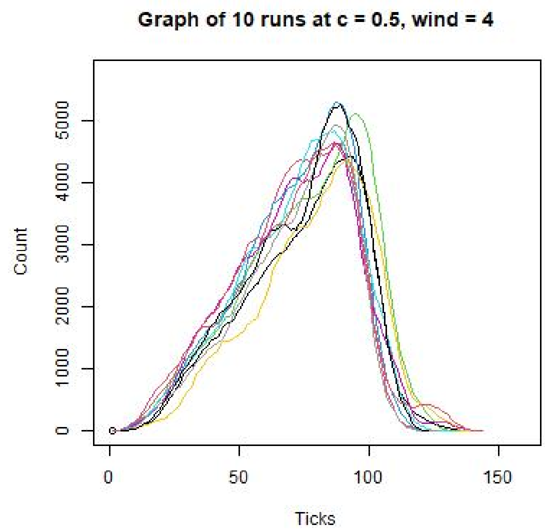


(c) All Fires and Embers

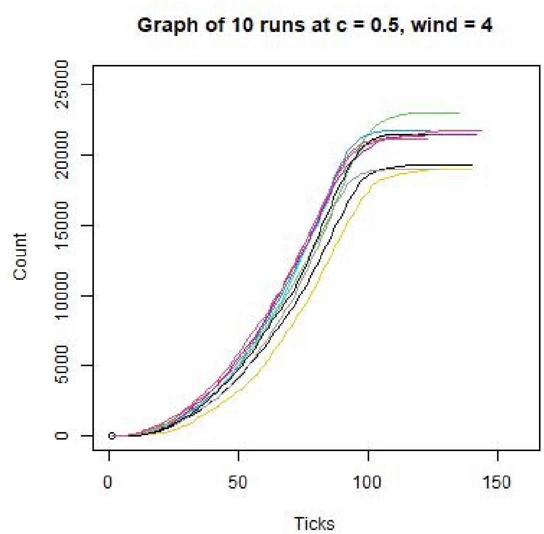
Figure B.6: The graphs show runs at a wind speed of 2 and a combustibility of 0.5. All the runs are different colors.



(a) Active Fires

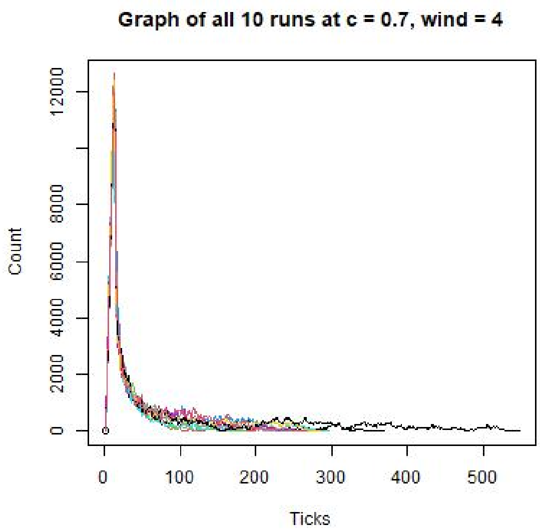


(b) Active Embers

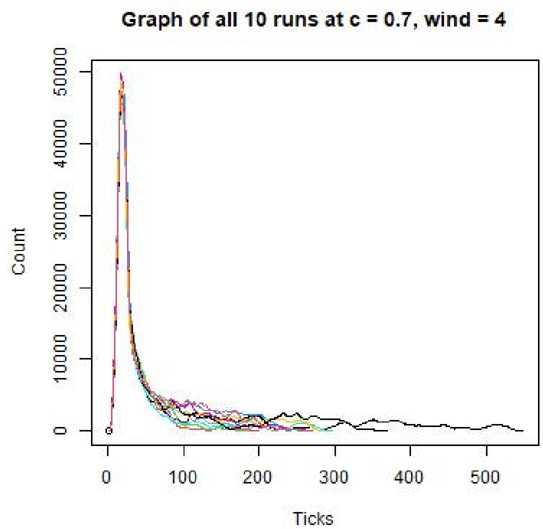


(c) All Fires and Embers

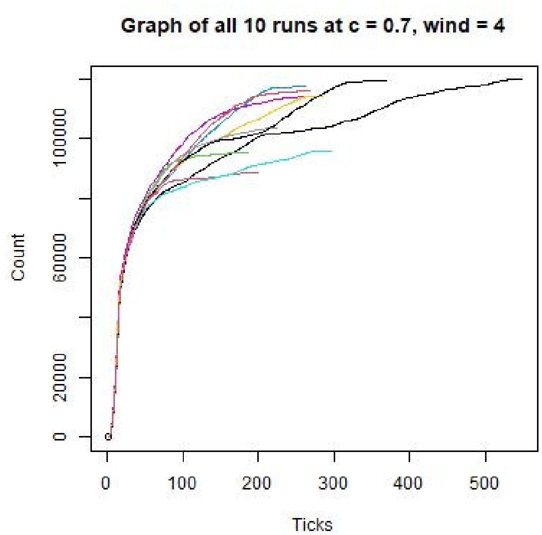
Figure B.7: Graphing all the baseline runs is not useful, so instead 10 runs were selected to be graphed. All fires and all embers are just graphed as a single line representing both.



(a) Active Fires

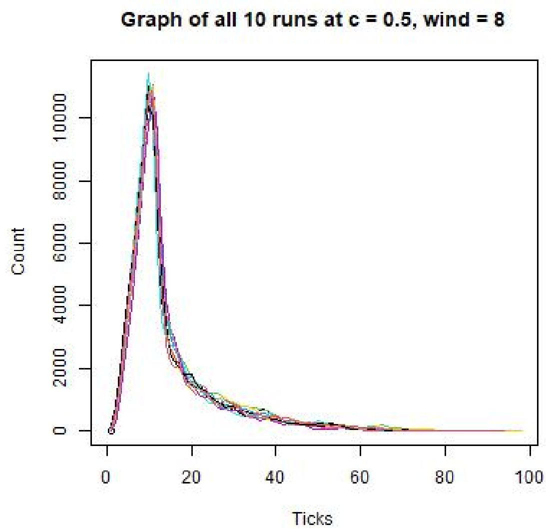


(b) Active Embers

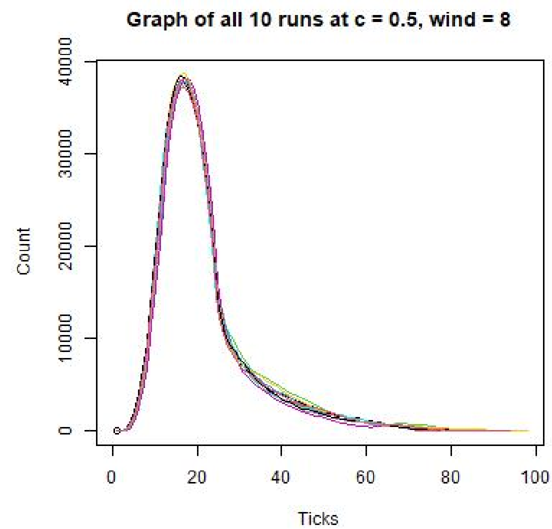


(c) All Fires and Embers

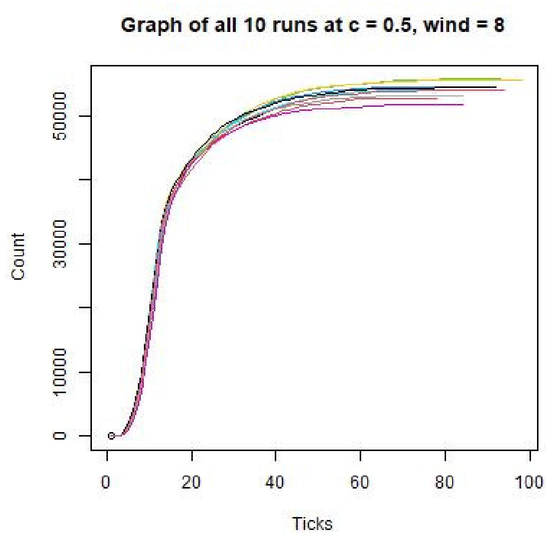
Figure B.8: The figures show the graphs of each of the different values monitored for a simulation with a combustibility of 0.7 and a wind value of 4. There is a clear outlier run (black line) which extends farther than the other graphs.



(a) Active Fires



(b) Active Embers



(c) All Fires and Embers

Figure B.9: The figures show the graphs of each of the different values monitored for a simulation with a combustibility of 0.5 and a wind value of 8.

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