

Modeling How Moisture Affects Wildfire Spread

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Abstract

Wildfires are a massive threat with many different factors that make predicting their spread significantly harder. To combat this, it is prudent to focus on one aspect at a time to better understand the parts before the whole. This paper focuses on how moisture affects the wildfire propagation. Moisture is a key component in fire propagation, as surfaces that are wet will have a harder time catching fire. However, the heat from the fire will dry out the moisture. The wildfire propagation is explored through the use of a matrix grid, one starting fire in the center, and allowing that fire to spread to other neighboring spaces with a set ignition probability. When neighboring spaces fail to catch fire, the moisture level is reduced by a fixed drying factor. As moisture increases, fire propagation significantly slows, yet the moisture effect is lessened when drying is taken into account. While not an exhaustive understanding of fire propagation, moisture and drying do have an important impact on the spread of a wildfire.

1 Introduction

Wildfires represent a significant and frequent natural disaster in California. However, accurately mapping the propagation, or spread, of wildfires is challenging due to the large amount of factors involved. One such factor to be considered is the moisture level of the environment during a wildfire. In the context of wildfire management, moisture is a critical factor influencing fire propagation. Moisture content, which refers to the amount of water within potential sources for fire fuel such as vegetation, should directly affect their combustibility. Dead vegetation is extremely dry and is known to burn very easily, while wet plants often burn poorly. This leads to the assumption that lower moisture theoretically makes for easier ignition and faster spread. Accurate mapping of these moisture levels would then be vital for predicting fire behavior and implementing effective wildfire management strategies. To better understand fire propagation in this regard, I have focused on a simplified version of the spread that takes varying moisture levels into account.

In modeling this problem, I am assuming that as fire spreads from one tree to its neighbor, the presence of moisture within these trees inherently makes them resistant to ignition. I am also taking into account that as the fire spreads towards these trees, the heat generated causes the moisture to evaporate. This paper, and the work contained in it, is designed around answering the following question: do moisture, and the drying effect of a wildfire on said moisture, have a significant impact on the propagation of a wildfire?

2 Model

For my model, I am using a numerical algorithm, based on a cellular automaton, which propagates the fire from one cell to its neighbor using specific probability rules. I initiate the simulation with an empty grid featuring a singular starting point of fire. The fire has a set chance to spread one space in any direction, known as the ignition probability. Furthermore, the fire will only spread to spaces immediately adjacent to the existing flames. In my numerical algorithm, I relate a random variable to my ignition probability.

The comparison that is made for a fire to propagate to a nearby space is given by

$$R \leq p, \quad (1)$$

where R is a random value between 0 and 1 while p is the ignition probability, and if R is less than or equal to p, the cell ignites.

In the presence of moisture (characterized by a scalar m , so that high moisture = 1 and no moisture = 0), the new probability of ignition is simply $p(1 - m)$. Spaces next to a fire that do not ignite experience moisture reduction from one timestep to the next according to:

$$m_{t+1} = m_t/d. \quad (2)$$

The d in (2) represents the drying factor, illustrating how areas that don't catch fire dry out over time and become more susceptible to future ignition.

3 Method

3.1 Process

In the numerical algorithm, the propagation is broken up into separate timesteps that are intended to replicate the passage of time. The process starts by setting the center square in the grid to a value of 1 while every other space has a value of 0, with a 1 representing a space that is on fire and a 0 representing a space that is unlit. The algorithm then proceeds by iterating over every space within the grid to find all the spaces currently on fire. For each unlit space adjacent to a lit one, the possibility of the unlit space catching fire is evaluated using (??). If an unlit space catches fire, the space in the grid is marked as on fire. In cases where an unlit space does not catch fire, the heat exposure causes a reduction of moisture according to (2). The evaluation and recording of all spaces in a grid marks one timestep.

The algorithm iterates for 10 iterations, and to ensure accuracy, the same simulation is repeated 1000 times and averaged to help eliminate the randomness of the spread. After all the fire propagation has been iterated through entirely, I then sum the values in each cell along each timestep. These values serve as the area of the fire propagation, which I then graph against my timesteps to produce my results in the next section.

3.2 Verification Method

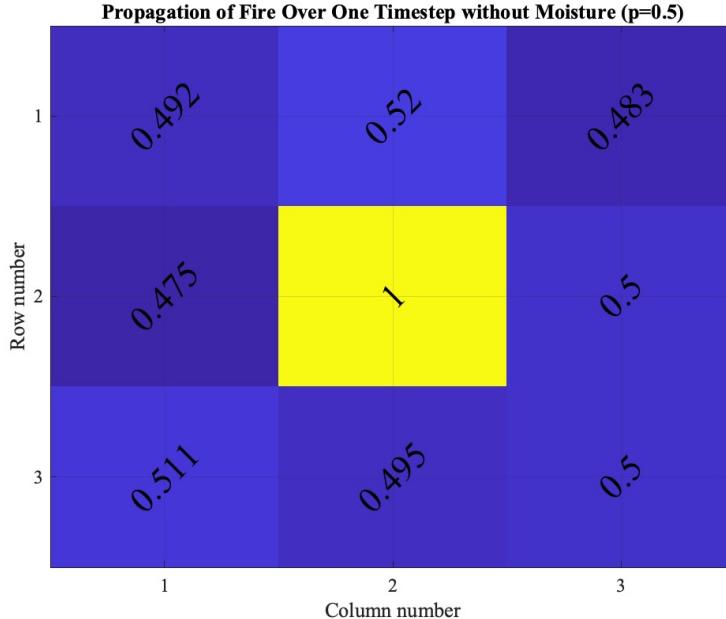


Figure 1: This image shows a 3x3 grid with the center value being 1 and the values around it being close to 0.5. This is the computational representation of the fire propagation without moisture after one iteration of time. This single timestep was repeated 1000 times and averaged to create the resulting values.

To verify this fire propagation, I put my computational model against the analytical solution. In the absence of moisture, analytically speaking, using an ignition probability of 0.5, after one timestep the center should have a value of 1 and the surrounding values should have a value of 0.5. The computational model, shown in Figure 1, shows a value of 1 in the center and values of around 0.5 in all the spaces surrounding it. While not exactly 0.5, the values are all relatively close enough to be accurate.

In a similar fashion, I modeled the propagation of the fire propagation with moisture over 1 timestep. Analytically, with an ignition probability of 0.5 and moisture level of 0.5, this should have a value of 1 in the center with a value of 0.25 everywhere else (calculated through the use of the modified ignition probability when moisture is present outlined in the model section). Figure 2 shows that the computational model has a center value of 1 and values around the ignition point have values around 0.25. This proves that our model accurately represents the propagation with moisture.

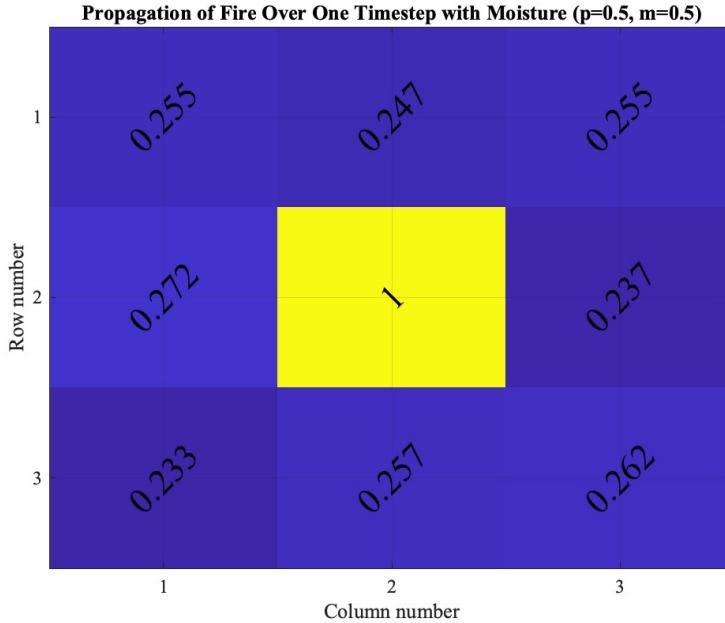


Figure 2: This image shows a 3x3 grid with the center value being 1 and the values around it being close to 0.25. This is the computational representation of the fire propagation with moisture after one iteration of time given that the ignition probability is 0.5 and the moisture level is 0.5. This single timestep was repeated 1000 times and averaged to create the resulting values.

4 Results

4.1 No Moisture and No Drying

To explore the initial propagation without moisture over three distinct ignition probabilities, 25, 50, and 75 percent, I mapped the spread over 10 iterations and graphed the number of spaces on fire. The results are shown in Figure 3 which presents how fire spreads without moisture across a grid over multiple iterations, depending on different ignition probabilities. There are three lines on the graph, each representing a different ignition probability. The x-axis, ranging from 1 to 10, represents the number of iterations, while the y-axis, ranging from 0 to 350, represents the average number of grid cells that are on fire. The first line, in blue, represents an ignition probability of 25 percent. It starts at 1 and curves gently upwards as it moves to the right, indicating a relatively slow and steady increase in the number of grid spaces burning over time. The second line, in red, represents an ignition probability of 50 percent. This curve moves upwards more steeply, suggesting a faster rate of fire spread. The third line, in yellow, represents an ignition probability of 75 percent and rises sharply as it moves right, demonstrating the quickest spread among the three, with the number of burning grid spaces increasing

rapidly with each iteration. The graph implies that with higher ignition probabilities, the fire spreads more rapidly and affects more grid spaces over time. There is a clear link between higher p values and higher numbers of spaces on fire. Ignoring moisture ensured that the differences in fire growth rates could be directly attributed to the varying ignition probabilities.

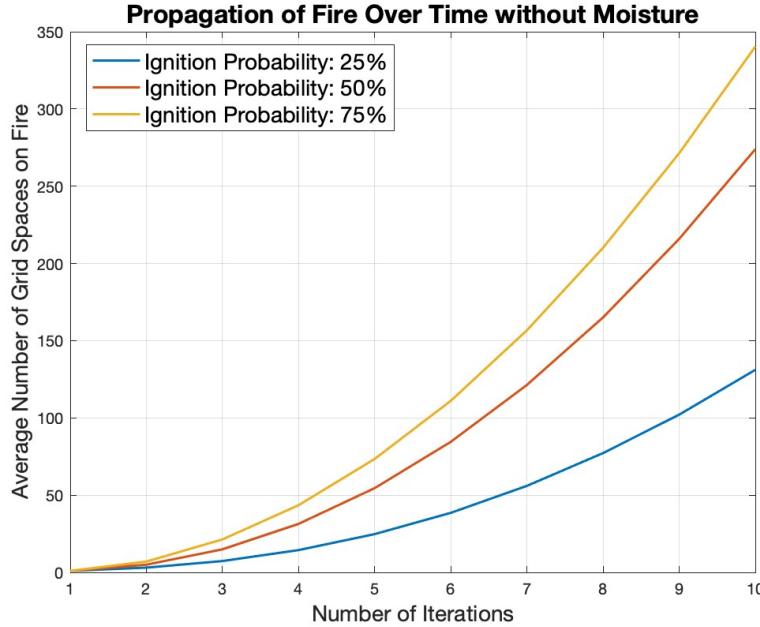


Figure 3: Graph shows the propagation of fire based on the average number of grid spaces that caught fire per iteration, regardless of moisture and drying. Three different spreads are shown, each with a differing ignition probabilities.

4.2 Moisture without Drying

In a similar fashion, I modeled the fire propagation with moisture but still without drying. Ignition probability was fixed to be 0.5 for this study. The results are shown in Figure 4, which again shows the area of the fire as a function of time, for four different experiments with four distinct moisture levels (0, 0.25, 0.5, and 0.75) to provide an understanding of how varying moisture content impacts the fire propagation. The first line, in blue, represents a moisture level of zero percent and shows a steep rise, indicating rapid fire spread. The second line, in red, signifies a 25 percent moisture level and has a more moderate slope. The third line, in yellow, corresponds to a 50 percent moisture level and rises even more gently, suggesting an even slower fire spread. The fourth line, in purple, is for a moisture level of 75 percent and is the flattest, indicating the most significant dampening effect on fire spread. This trend was consistent across the range of moisture levels tested, demonstrating a clear correlation between increased moisture and decreased fire propagation.

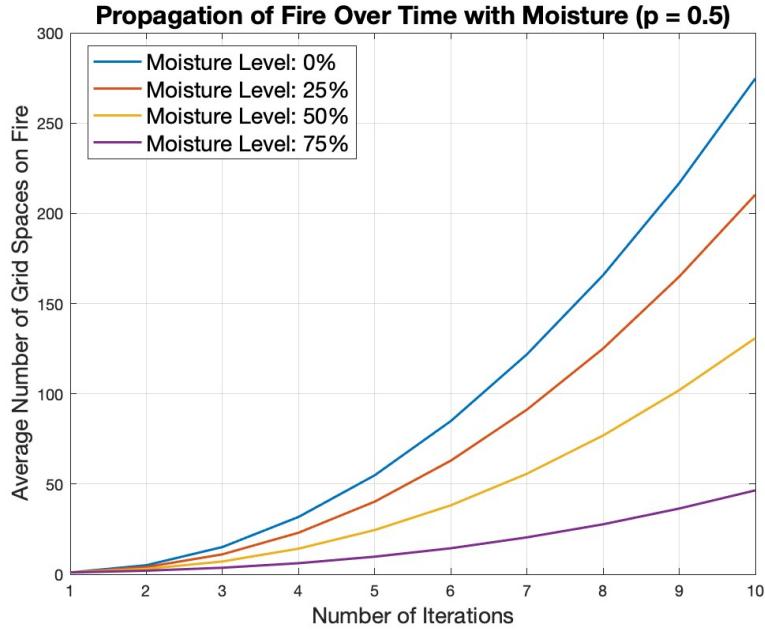


Figure 4: Graph shows the propagation of fire with moisture based on the average number of grid spaces that caught fire per iteration. Four different spreads are shown, each with an ignition probability of fifty percent, but varying moisture levels of 0, 0.25, 0.5, and 0.75.

4.3 Moisture with Drying

Lastly, I evaluated the effects of fire-induced drying on the propagation. The graphed model in Figure 5 (which again shows the area of the fire as a function of time), explores the varying drying factors with a significant moisture level (0.75) and an ignition probability of again 0.5. There is also one reference scenario that is devoid of moisture entirely. The graph displays five lines, each illustrating the rate of fire spread under different conditions of moisture drying. The first line, in blue, marks the reference and shows a sharp ascent, serving as a control for comparison and depicts rapid fire spread in the absence of moisture. The second line, in red, shows the effect of consistent moisture without drying, leading to a significantly shallower curve than the reference. Subsequent lines represent different drying factors, with a drying factor of 2 in yellow, drying factor of 4 in purple, and drying factor of 8 in green. Each line is progressively steeper than the last, indicating that as the drying factor increases, the rate of fire spread accelerates due to the reduction in moisture slowing down the fire. The green line, with the highest drying factor, is still much lower than the reference blue line, demonstrating that any moisture, even with drying, inhibits fire spread to some degree. While the drying factor has a significant impact on the fire propagation and increases the area of fire significantly, higher drying factors have lessening impact. Additionally, the fire propagation is not as fast as in the case devoid of moisture entirely. This is likely due to the delayed effect of the drying. Even with really high drying factors, the base moisture level of 0.75 still has a significant impact until it is dried. So, the reference line with no moisture can propagate much further in the ten iterations since it takes a timestep to dry moisture.

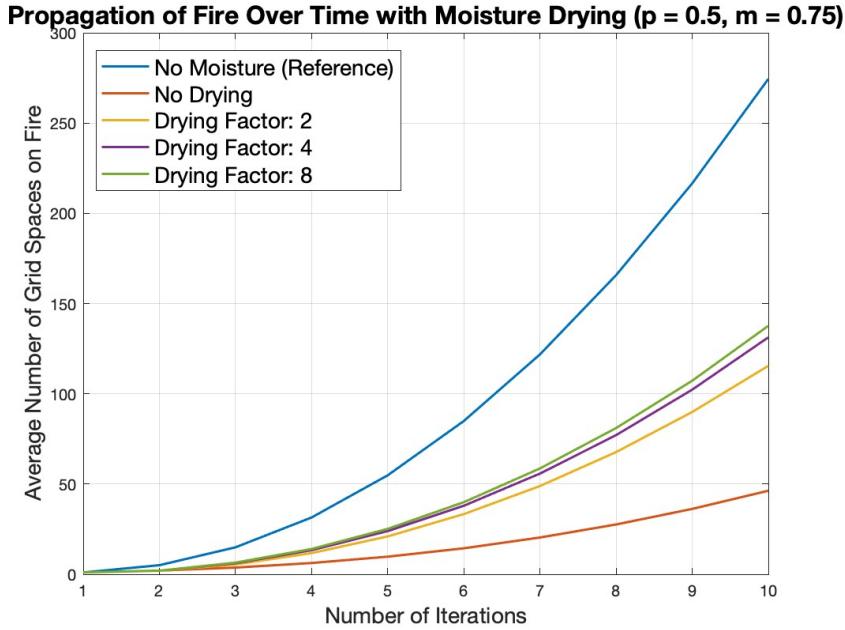


Figure 5: Graph shows the propagation of fire with moisture and drying based on the average number of grid spaces that caught fire per iteration. Five different spreads are shown, each with an ignition probability of fifty percent. The first line has no moisture, and all others have a moisture level of 0.75, but varying drying factors of 1, 2, 4, and 8

5 Conclusion

5.1 Caveats and Future Work

While this study shows the impact of moisture and the drying of that moisture, there are multiple limitations on this model to ensure accuracy. One significant limitation is the assumption of constant moisture levels across the entire grid, a simplification given so that moisture can be studied universally as opposed to the often very real likelihood that moisture is different everywhere. This moisture can vary due to differences in vegetation or even simply vary over time as vegetation naturally dries out in the sun. A rainstorm, for example, moves in a fixed direction, periodically covering ground over time rather than a whole region at the same moment. Additionally, the model's treatment of drying effects on grid spaces immediately adjacent to fire overlooks the potential for this heat from a fire to cause the drying effect on a broader area. This was also done to ensure simplicity, but in reality fire would likely have a diminished drying effect on spaces further than those that it is directly adjacent to. Moreover, the constraint that fire can only propagate to directly adjacent spaces does not account for the ability of wildfires to leap across multiple spaces through wind or through embers. These caveats will be addressed in future work.

5.2 Take Home Messages

In this exploration of fire propagation dynamics, I have shown that the presence of moisture and its subsequent drying due to heat exposure play important roles in the behavior of wildfire spread. Despite simplifications made for the sake of model clarity, the simulations reliably demonstrate that higher moisture levels result in a decrease in fire propagation speed and area. Adding drying factors helps us understand how the heat from a fire can reduce moisture over time, making it easier for vegetation to catch fire later. While acknowledging that the model does not encompass the full complexity of real-world scenarios, these preliminary findings are nonetheless informative. They underline the significant influence moisture has as an inhibitor of wildfire progression. Both moisture and drying of moisture have a huge impact on wildfire propagation, so that should be a priority research area for the future.