Forest Fire Analytics: A Comprehensive Network Model Study

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1 INTRODUCTION

1.1 Motivation

Forest fire propagation prediction is inspired by the recent news on California forest fires [2]. There have been many historical reports about the fire frequency in California. In 2018 alone, 6188 fires have been reported by CalFire, affecting more than 1.02 million acres of forests/lands. In 2019, 4501 fires were reported from January to October, affecting 45,800 acres of forests/lands [6]. According to the National Interagency Coordination Center (NICC), as of October 8th, 45196 wildfires have burned 7928100 acres this year. This is 1.4 million more acres burned than the 10-year-average [1].

In this project, we are going to focus on analyzing the spread of forest fire in California. There is an increasing need for building an accurate fire propagation model to help mitigate the damage caused by forest fires. Our goal is to modify the model developed by Hajian et al.[3] and use the data of California to simulate fire propagation.

1.2 Related Work

Our project is related to the fire spreading modeling. Here we present some existing studies on this topic.

An interesting work that uses networks to model fire propagation is with the use of Cellular Automata (CA) [4, 9] . It is an intuitive physical model where time and space are discrete and that interactions are only local. In general, CAs are widely used to simulate catastrophic events. It is implemented using a raster representation of the landscape in which fire propagates from one cell to another based on a set of rules. Its simplicity and strong ability to simulate complex systems present to be a great asset. However, CAs pose some limitations. For one, CAs can only provide two-dimensional visualization methods. Furthermore, it mainly adopts only from heuristic methods to define transformation rules that are significantly influenced by subjective factors. Lastly, CAs suffer extremely from produced fire shape distortion. The model we would like to propose improves on this by taking into account the use of continuous values on the angle of the wind direction, as CAs are constrained to only working with eight possible compass directions.

In the study of Hajian, et. al.[3] , they briefly discussed how fire models can be categorized into physical models, empirical models, and math simulation models. In particular, they have made use of empirical models that use historical data to describe fire behavior and predict the wind's fire rate of spread (ROS). The paper also describes how wind speed is the main factor that affects fire spread, and that the mean wind speed can represent wind effect. However, the downside of this approach is its inaccuracy as wind is dynamic and unpredictable. A solution to this is likely to represent it as a random variable.

Furthermore, Hajian et al.[3] proposes a network-based approach to represent fire propagation paths on the landscape. Their team has framed the problem into one that can be solved using Stochastic Shortest Path Problem. However, the expensive computational cost of the problem gives rise to a better solution, that is, to use Monte-Carlo methods to derive empirical results. The Dijkstra's algorithm that computes for the shortest paths has been utilized and network reduction schemes have been applied to mitigate the computational burdens suffered by the algorithm. The stochasticity of the model and the use of Monte-Carlo simulations are the parts that we can make use of. Our project aims to use a modified version of this network model on our dataset.

The Rothermel's model [8] was used to compute the rate of spread (ROS) in Hajian et al.'s network model. Rothermel's equations incorporate randomness and takes fuel (various attributes such as depth, moisture, and so forth) and weather (wind speed in particular) as the inputs. This model demonstrates the quantitative relationship between the fire environment and the rate of spread (ROS) which is capable of efficiently predict the fire behaviour.

Small world network (SWN) models have also been used to study fire spread through forest fuels. Porterie et al.[7] studies fire spread through short-range (nearest neighbor) and long-range (spotting effects). The dynamics of the SWN model and percolation methods were also discussed. The edge offered by this paper is that it takes into account long-range spotting effects caused by fire, which has not been considered by previous works. This particular model can also be applied to our dataset, and compare it with other aforementioned models.

1.3 Problem Definition

Given a map (includes forests, villages, etc.), we would like to construct a network that can be used to make predictions, analyses, and conclusions on forest fire analytics. For the first stage of our analysis, we would like to perform prediction on forest fire propagation. In this stage, we also aim to understand how various factors impact fire propagation. These factors include weather (wind direction, speed, temperature), nature (vegetation), human-related (construction, human activities). Using this method, we simulate the spread of forest fires to display the affected areas, the direction of the fire spread, and the size of the fire.

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The second stage of our study (time-permitting) involves the prediction of fire arrival time to villages and places of human activities (through wind speed). If in the first stage, we examine simulations that begin from a single source of ignition point, in this stage, we investigate those that generate fires from multiple ignition points. Finally, an interesting addition to our work includes the proposition of intervention strategies to stop the spread of fire. Some of these strategies include the addition of more fire zones, the consideration of material used in houses in villages, and so forth.

2 METHODOLOGY

2.1 Network Construction

Wildfire spread analytics are related to mining spatial data over a period of time. The process of wildfire spreading happens from the ignition geolocation to its neighbors and then to its other neighbors, and so forth. If we consider geolocations as points, given an observation area, fire propagation can be seen as a dynamic progression of two recognizable stages: active point (on-fire) and inactive point (not on-fire). In our project, the network nodes represent certain points of homogeneous sub-regions and the network edges represent the travel paths of the fire. On the top of that, we will utilize different node colors to represent villages and communities in the area.

2.2 Modelling Fire Propagation

The first problem we want to address is that given the wind and terrain conditions, predict how the fire propagates starting from the ignition point. To address it, we will model it by identifying the stage of each nodes. The modeling allows to (1) predict the wildfire pattern and final shape based on a set of rules, (2) estimate the probability of villages being affected by the fire, (3) in the event that there are multiple ignition points, predict the fire propagation and final shape.

2.3 Estimation of Travel Time

The second problem is to predict the distribution of the fire arrival time given the ignition point (source) and the point of interest (destination) as represented by two of the nodes in the network, namely v_s and v_t. We utilize a stochastic fire spread model developed by Hajian et al, in which the wind speed and the fire rate of spread are modelled as random variables to account for its variability.

2.4 Wildfire Fighting Strategies

Based on the result of fire propagation simulation, we study the problem of wildfire fighting tactics and support warning to the population. In the first problem (fire fighting tactics), we determine some areas that need more fire zones. As such, fire spread will be mitigated and can slow down. In the second problem (fire warning), based on the estimated fire travel time, we identify the proper time used to warn residents living in the high-risk area. As a result, the number of deaths caused by wildfire can be minimized.

3 EVALUATION

3.1 Datasets

Our team was able to find the OSPO [5], a database that records information on forest fires in the U.S. For any given day (in the past), we can extract information such as geolocation coordinates of fires, the exact time of ignition, the fire radiant power, etc. Furthermore, we have found that the use of the Google Map Satellite as another potential source for map data. The idea is to divide the region of California into several subregions and that the centroid of each subregion will serve as the geolocations of consideration, and eventually the network's nodes.

3.2 Visualization

To improve the understanding of the analysis, we will provide rich visual analytics about how wildfires spread given an area and the risk of each village getting caught on fire. In particular, we will provide detailed diagrams of final fire shapes under different conditions such as wind direction, wind speed, etc. We will also provide detailed diagrams of village analytics over time (fire risk).

3.3 Robustness and challenges

First, we will set different parameters (wind direction, wind speed) on the same dataset to simulate fire propagation under different conditions. Then we will do the experiment using other models to compare the results from running different models. Regarding challenges, along with challenges of accurate modeling, there are several other technical challenges that need to be addressed in the project. The most important one is related to scalability: as the map becomes bigger, the network we construct is going to be massive, but the simulation needs to be able to provide results in a short running time.

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