Environmental Modelling & Software 82 (2016) 73–88

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Modeling wildfire propagation with the stochastic shortest path: A fast simulation approach

Mohammad Hajian*, Emanuel Melachrinoudis, Peter Kubat

Department of Mechanical and Industrial Engineering, Northeastern University, Boston, MA 02115, United States

ARTICLE INFO

Article history:
Received 17 December 2015
Received in revised form
28 March 2016
Accepted 30 March 2016

Keywords:
Shortest path
Stochastic modeling
Wildfire propagation
Network size reduction

ABSTRACT

Wildfires have significant environmental and economic effects. Since containment of wildfires involves deciding under tight time constraints, there is an increasing need for accurate yet computationally efficient wildfire prediction models. We consider the problem of finding the fire traversal time across a landscape considering wind speed as an unpredictable phenomenon. The landscape is represented as a graph network and fire propagation time is modeled as the Stochastic Shortest Path problem. Monte-Carlo simulation is utilized to determine the fire travel-time distribution. A network size reduction methodology is introduced to quicken the simulation time by eliminating the unimportant parts of the network. This methodology is implemented in Java to simulate the wildfire propagation on a study area located in Massachusetts. This method shows the capability of substantially reducing the simulation time without affecting prediction accuracy, enabling the algorithm to serve as a fast and reliable tool for fire prediction.

1. Introduction

Wildfires have significant short-term and long-term local economic effects, with larger fires generally having serious longer-term impacts. Wildfires can directly restrain recreation and tourism. They can cause significant damage to infrastructure and facilities located at the wildfire-urban interface. Extensive fire damage to trees can significantly alter the timber supply and water supplies can be degraded by post-fire erosion. If an area's aesthetics are impaired, local property values may decline. On average, more than 100,000 wildfires burn 4 to 5 million acres (1.6–2 million hectares) of land in the U.S. every year (NG, 2014). Predicting the fire arrival time to a point of interest can greatly help in choosing the mitigation strategy and preparing to evacuate in-danger areas before the fire's arrival. A precise estimate of the fire perimeter and fire spread rate makes it possible to determine the optimal escape routes.

In this paper, we present a stochastic fire spread model capable of accounting for the unpredictable changes in the wind speed. The model provides a stochastic time frame with associated probabilities for the wildfire arrival time at a point of interest, e.g. residences, firemen camp, etc. This in turn determines the reliability of the provided arrival times and helps the decision maker in adopting the best action plan.

2. Background

The focus of this paper is on fire propagation through a surface fire, i.e. the fire that burns fuels located at ground level such as leaf litter and fallen branches (Alexander and Cruz, 2011). Surface fires can have surprisingly huge impacts on forest floor vegetation, and can greatly increase the likelihood of far larger fires that can lead to complete destruction of a forest (Laurance, 2003).

According to Sullivan (2007c) classification scheme, there are three categories of surface fire models: 1) physical models, 2) empirical models, and 3) mathematical analogous and simulators. Physical models are those concerned with the mathematical analysis of the fundamental physical and chemical processes of fire spread. Empirical models are those developed from historical wildfire studies or from experiments and observations. The focus of empirical models is on the key characteristics that describe the fire behavior. The primary use of such models has been to predict the fire Rate Of Spread (ROS) in the direction of the wind (Sullivan, 2007a).

One of the widely used models in this category is the Rothermel's model (Rothermel, 1972) which forms the basis of National

* Corresponding author.
E-mail address: hajian.m@husky.neu.edu (M. Hajian).

http://dx.doi.org/10.1016/j.envsoft.2016.03.012
1364-8152/

Fire Danger Rating System (Scott and Burgan, 2005) and also the fire prediction tool BEHAVE (Sullivan, 2007a). The Rothermel's model is able to predict ROS, taking into account fire environmental factors such as the mean wind velocity, slope of the terrain, propagating flux and fuel characteristics. Other researchers have also tried to establish a quantitative relationship between the fire environment and the ROS to predict the fire behavior. To name a few: Fernandes et al. (2002) considering mediterranean pine trees (pine pinaster), Cheney and Gould (1995) grassland, Marsden-Smedley and Catchpole (1995) buttongrass and Cruz et al. (2013) who used non-linear regression analysis for ROS prediction.

In the third category of fire models, the focus is on the simulation of fire spread across the landscape from a holistic perspective. The models in this category are generally concerned with predicting the wildfire pattern and final shape in addition to estimating its behavior. Most of the simulation software packages and tools fall into this category. Finney (2004) developed FARSITE area simulator based on the BEHAVE fire prediction system (Sullivan, 2007b). BEHAVE (Finney, 2004) is a fire behavior prediction and fuel modeling system based on Rothermel's model and consists of two main components, FUEL (Burgan and Rothermel, 1984) and BURN (Andrews, 1986). FARSITE is the most commonly used and widely recognized deterministic fire growth modeling system (Massada et al., 2011) and is used by the National Park Service, U.S. Forest Service, and other federal and state land management agencies (FARSITE, 2014). FARSITE is not only a fire prediction tool but also a system that supports warning to population and defining fire fighting tactics. Other fire simulators include IGNITE (Green et al., 1990), FIREMAP (Vasconcelos and Guertin, 1992), FlamMap (Finney, 2006), Prometheus, FIRE!, DYNAFIRE, PYROCAT, FireMaster (Fernandes et al., 2002) and FireStation (Lopes et al., 2002).

Cellular Automata (CA) is another methodology that has been widely utilized for simulation of catastrophic events such as wildfire. CA is implemented using a raster representation of the landscape in which fire propagates from one cell to another based on a set of rules (Peterson et al., 2009). Researchers have tried to increase the accuracy and speed of CA-based algorithms via various methods such as changing the shape of the cells (Trunfio, 2004), taking advantage of parallel processing (Karafyllidis, 2004), using fuzzy logic (Mraz et al., 1999) and stochastic modeling of CA (Almeida and Macau, 2011). The main weakness of CA is that it can suffer from distortion of the produced fire shape. Ghisu et al. (2015) tried to mitigate this problem by modifying the fire spread equations in an optimal CA model.

Cova et al. (2005) utilized a network-based representation of fire spread, associating network arcs with fire spread times to determine the evacuation buffer. Dijkstra's shortest path algorithm was employed to calculate the fire travel time through the network. The Shortest Path (SP) problem is one of the best-known combinatorial optimization problems. In graph theory, the shortest path problem is defined as the problem of finding a path between two vertices in a graph in a way that the sum of the weights of edges comprising the path is minimized. Dijkstra's algorithm is able to find all the shortest paths between a given source node and all the other nodes in a network. Stepanov and Smith (2012) represented a heterogeneous fire landscape as a network and used Dijkstra's algorithm to estimate the minimum fire travel time paths from ignition points to specific points of interest.

Although the wildfire literature is rich on deterministic models, uncertainty analysis in fire modeling is a rarely studied topic. Bachmann and Allgwer (2002) applied first-order Taylor series to Rothermel's equations to compare the variation of input uncertainty to output uncertainty. They recognized the wind speed as one of the most important contributors. In a recent study, Hilton et al. (2015) investigated the variation of wind speed, wind direction and combustion conditions on the fire perimeter rate of propagation. Hargrove et al. (2000) developed a probabilistic tool called EMBYR to simulate large fires through heterogeneous landscapes by calculating transfer probabilities between cells on a grid network. Boychuk et al. (2009) developed a stochastic fire growth model on a grid utilizing continuous-time Markov-chain in which the rate of fire spread in each cell of the grid was considered to be exponential.

In this study we consider uncertainty propagation in a network-based representation of the landscape. Random variables are used to represent the fire rate of spread in the network with the goal of finding the minimum fire travel time probability distribution between an ignition point (source) and a point of interest (destination). We have developed a simulation model to account for the variability of the wind, which is one of the most important factors in wildfire spread. Our method provides the ability to speed up the simulation process to make the algorithm computationally reliable and efficient for real-time wildfire events.

3. Materials and methods

3.1. Study area

The Montague Plains Wildlife Management Area (MPWMA) in West-Central Massachusetts was selected as the study area for this research due to the availability of fire data, which was first provided by Duveneck (2005), and later studied by Stepanov and Smith (2012). The MPWMA is owned and managed by the Massachusetts Department of Conservation and Recreation (DCR) Division of Fisheries and Wildlife (DFW) in cooperation with Northeast Utilities (NU). The primary purposes of the site are to preserve and protect an outstanding example of pine-scrub oak barrens, which occur throughout the Northeast from New Jersey to Maine. The barrens are characterized by excessively drained soils and by several plant species which are highly flammable (Clark & Patterson III, 2003). The site also provides an area for wildfire viewing and scientific research.

The pink area in Fig. 1a shows the location of the Franklin County, in the Commonwealth of Massachusetts within which the red area is the town of Montague. A magnified view of Montague with its Wildlife Management area is depicted in Fig. 1b.

3.2. Predicting the fire propagation time

Fire propagation rate depends on fuel characteristics, terrain, and weather, which are the three fire environment factors. Among the weather factors, the surface wind speed is one of the main factors affecting the fire rate of spread (Marsden-Smedley and Catchpole, 1995). In fire models, the mean wind velocity is typically used to represent the wind effect. However, this is not an accurate representation as wind is dynamic and changes quickly. We propose a wildfire propagation model in which the wind speed and accordingly the fire rate of spread are modeled as a random variable to account for the variability of the wind speed. It should be noted that we modeled the wind speed based on the predominant wind speed and our model does not account for the effect of fire-induced winds.

Fig. 2 depicts a high-level schematic of our proposed model. A network-based approach is used to represent the fire possible propagation paths on the landscape.

3.3. Network construction

Our network is a graph consisting of a set of nodes V and a set of edges E. In our model, the network nodes represent certain points