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Innovative Applications of O.R.

A maximal covering location-based model for analyzing the vulnerability of landscapes to wildfires: Assessing the worst-case scenario

Eghbal Rashidi[a,*], Hugh Medal[a], Jason Gordon[b], Robert Grala[b], Morgan Varner[c]

[a] Department of Industrial and Systems Engineering, Mississippi State University, Starkville, MS 39762, USA
[b] Department of Forestry, Mississippi State University, Starkville, MS 39762, USA
[c] Department of Forest Resources and Environmental Conservation, Virginia Tech, Blacksburg, VA 24061, USA

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A B S T R A C T

In this research, we study the vulnerability of landscapes to wildfires based on the impact of the worst-case scenario ignition locations. Using this scenario, we model wildfires that cause the largest damage to a landscape over a given time horizon. The landscape is modeled as a grid network, and the spread of wildfire is modeled using the minimum travel time model. To assess the impact of a wildfire in the worst-case scenario, we develop a mathematical programming model to optimally locate the ignition points so that the resulting wildfire results in the maximum damage. We compare the impacts of the worst-case wildfires (with optimally located ignition points) with the impacts of wildfires with randomly located ignition points on three landscape test cases clipped out from three national forests located in the western U.S. Our results indicate that the worst-case wildfires, on average, have more than twice the impact on landscapes than wildfires with randomly located ignition points.

1. Introduction

Although natural fires are part of many terrestrial ecosystems (Ryan, Knapp, & Varner, 2013), uncontrolled wildfires can be destructive and can cause loss of human life and property (Minas, Hearne, & Martell, 2014). Destructive wildfires are a primary concern in places where major cities are located close to highly flammable vegetation areas, such as the Western and Southern U.S., Australia, and Mediterranean Europe (Minas et al., 2014). There has been a sharp increase in fire events across the globe (Minas, Hearne, & Martell, 2013), and the destruction caused by wildfires appears to be worsening (Minas, Hearne, & Handmer, 2012). From 2002 through 2011, wildfires in the U.S. accounted for 13.7 billion dollars in total economic losses, a 6.9 billion dollars increase from the previous decade[1] (Haldane, 2013). The deaths of 19 firefighters in 2013, the largest such loss since 1933, were part of a general trend of rising threats to lives as well as properties (Haldane, 2013).

Wildfire risk has increased with human populations reaching further into wildlands. About 32% of housing units including homes, apartments and buildings in the U.S. and 10% of all lands with houses are situated in the wildland–urban interface (WUI; the zone of transition between natural land and human development) (Radeloff et al., 2005), and WUI is expected to continue to grow (Hammer, Stewart, & Radeloff, 2009). Homes located in the WUI have a high probability of exposure to wildfire, regardless of vegetation type or potential fire size (Stein et al., 2013). Along with increasing wildfire risk, the costs associated with wildfire management are increasing. The United States Department of Agriculture (USDA) reported that more than 1.6 billion dollars is spent annually by state forestry agencies on wildfire protection, prevention, and suppression (Stein et al., 2013). To reduce the consequences of catastrophic wildfires, planning effective mitigation programs is essential.

Risk assessment has increasingly become a key input to wildfire prevention and mitigation decision making processes (Ager, Vaillant, Finney, & Preisler, 2012; Calkin, Thompson, Finney, & Hyde, 2011; Haas, Calkin, & Thompson, 2013; 2015; Scott, Thompson, & Calkin, 2013). Miller and Ager have reviewed the recent advances in risk analysis for wildfires management (Miller & Ager, 2013). Determining the vulnerability of a system is an important component of risk assessment, which is employed to help develop risk mitigation strategies to counter risks (Ezell, 2007). Vulnerability assessment studies identify weak points in the system, and focus

* Corresponding author.
E-mail address: er442@msstate.edu (E. Rashidi).
[1] These values are not adjusted for inflation.

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on defined threats that could compromise the system's ability to meet its intended function. To our knowledge, no risk assessment study has considered the worst-case wildfires, and there has not been any pilot risk assessment for a potential arson-induced wildfire that utilizes coordinated multiple ignition points. The results of such a study can be used in strategic planning efforts for risk mitigation against a threat, especially when available resources and funds are limited. This paper aims to fill this gap by proposing a mathematical programing model to study the vulnerability of landscapes to wildfires in the worst-case scenario.

Operations Research (OR) specialists have worked with fire managers to develop decision support systems that can help improve fire management; however, there remain substantial gaps between wildfire managers' needs and the decision support systems used (Martell, 2007). Linear programing and mixed integer programing (MIP) have been frequently used in wildfire management (e.g., Armstrong, 2004; Dimopoulou & Giannikos, 2001; Donovan & Rideout, 2003; Finney, 2008; Higgins, Whitten, Slijepcevic, Fogarty, & Laredo, 2011; Hof & Omi, 2003). Other approaches such as heuristics (Acuna, Palma, Cui, Martell, & Weintraub, 2010; Bettinger, 2010b; Bettinger, Boston, Kim, & Zhu, 2007; González-Olabarria & Pukkala, 2011; Kim, Bettinger, & Finney, 2009), nonlinear programing (González, Pukkala, & Palahí, 2005), goal programing (Calkin, Hummel, & Agee, 2005), stochastic programing (Arrubla, Ntaimo, & Stripling, 2014; Hu & Ntaimo, 2009; Ntaimo, Arrubla, Stripling, Young, & Spencer, 2012), stochastic dynamic programing (Konoshima, Albers, Montgomery, & Arthur, 2010; Konoshima, Montgomery, Albers, & Arthur, 2008), and robust optimization (Haight & Fried, 2007; Mercer, Haight, & Prestemon, 2008) also have been used in wildfire management. There have also been some simulation-optimization applications in wildfire research (e.g. Dimopoulou & Giannikos, 2004). Interested readers can find some review papers regarding the applications of OR in wildfire management; e.g. Bettinger (2010a), Martell (2015), Minas, Hearne, and Handmer (2012). In this research, we develop a mathematical programing model to evaluate the maximum impact of a wildfire on a landscape. We use the model to analyze the vulnerability of landscapes to wildfires based on the impact of the worst-case scenario ignition locations.

Although wildfires can start from anywhere on a landscape, the location and number of ignition points can be an important factor that impact the resulting wildfire spread. Using our developed optimization model, we investigate the effect of ignition locations on wildfires and identify the potential ignition locations which result in a wildfire with the maximum impact on a landscape. To model wildfire's behavior on a landscape, we use FlamMap (Finney, 2006), a fire behavior mapping and analysis program. We consider wildfires that contain a single and multiple ignition points, such as wildfires caused by lightning (Narayanaraj & Wimberly, 2012). The proposed model is then used to evaluate the impact of wildfire on three landscape test problems clipped out of three national forests in the Western U.S.

We believe this to be the first study that analyzes the worst-case vulnerability of landscapes to wildfires with regard to the location of ignition sites. Our ultimate goal in this paper is to evaluate the impact of the worst-case wildfires and to assess the vulnerability of landscapes to these wildfires. Identifying the highly vulnerable areas of landscapes can help wildfire managers in wildfire risk mitigation planning such as fuels treatment scheduling and fire suppression preparedness planning.

The remainder of the paper is organized as follows: Fire modeling details and the proposed mathematical model are presented and explained in Section 2. In Section 3, the model's functionality is tested on three landscape test problems, and the results are presented. Finally, Section 4 discusses the results and implications of our research.

2. Problem description and model formulation

2.1. Problem description

Our objective is to identify ignition locations of a wildfire that pose the maximum damage to the landscape. Damage or impact (used interchangeably through this paper) can be evaluated as the percentage of the landscape burned, or the value lost to fire. For the latter, the value of vegetation type, e.g. commercial timber, and the value of wildland–urban interface (WUI), if any, are used. We consider a landscape divided into a number of raster cells, and use FlamMap to model fire spread characteristics in each cell. If X is the set of vector x indicating the cell(s) from which a fire originates, and $f(x)$ is a function representing the corresponding impact of the fire on the landscape, then the research problem can be defined as identifying the ignition points, represented by vector x, of a fire that has the largest impact on the landscape, or equivalently to find x for which $f(x)$ is the maximum. We formulate the problem as a network optimization problem and later in Section 3 test it on three landscape test cases.

The primary assumptions for the research problem studied in this paper are as follows:

i. the ignition points of wildfires are randomly distributed across the landscape;
ii. multiple fires can start at any location in the landscape; however, for simplicity, we assume that the physical interaction of fires is negligible, and therefore fire behavior and characteristics do not change in presence of another fire;
iii. if multiple fires are ignited, they are all ignited at the same time and burn for the same duration and under the same fire weather conditions;
iv. the areas outside the boundaries are unburnable;
v. when wildfire reaches the center of a cell, that cell is assumed burned; and
vi. fire spreads in an elliptical shape within each cell.

2.2. Modeling the spread of wildfire

To model the spread of wildfire as a network optimization problem, we represent a landscape with a raster map divided into grid cells. If we represent the center of each cell as a node, and connect neighboring cells with directed arcs, then the landscape can be represented with a directed network (Fig. 1). As shown in Fig. 1 we use bidirectional arcs for modeling the spread of fire, implying that fire can burn up and down slopes and with and into the wind. To model the spread of fire in the landscape, we use the minimum travel time algorithm (MTT) (Finney, 2002) to analyze a scenario where multiple wildfires start at the same time across a landscape.

We use FlamMap to calculate the Rate of Spread (ROS) along with the major fire spread direction in each cell. The major fire spread direction in each cell represents the direction in that cell in which fires spread with the fastest speed. Fires can also spread along other directions, but at slower speed (Wei, 2012). We use formulas (1) and (2) to calculate ROS along other directions.

$$ROS = \frac{b^2-c^2}{b-c\times\cos(\theta)} \quad 0 \le \theta < \frac{\pi}{2} \tag{1}$$

$$ROS = \frac{b^2-c^2}{b+c\times\cos(\pi-\theta)} \quad \frac{\pi}{2} \le \theta < \pi \tag{2}$$

θ is the angle between major fire spread direction in each cell computed by FlamMap and the fire spread direction from this cell to the center of adjacent cells. In this formula b and c are outputs of FlamMap and are standard parameters used to describe the ellipse of fire spread. For more information we refer the reader to Green, Gill, and Noble (1983).