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Research article

Production and efficiency of large wildland fire suppression effort: A stochastic frontier analysis

Hari Katuwal [a,*], David E. Calkin [b], Michael S. Hand [b]

[a] The University of Montana, 32 Campus Drive, Missoula, MT 59812, USA
[b] Rocky Mountain Research Station, USDA Forest Service, 800 E Beckwith, Missoula, MT 59801, USA

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ABSTRACT

This study examines the production and efficiency of wildland fire suppression effort. We estimate the effectiveness of suppression resource inputs to produce controlled fire lines that contain large wildland fires using stochastic frontier analysis. Determinants of inefficiency are identified and the effects of these determinants on the daily production of controlled fire line are examined. Results indicate that the use of bulldozers and fire engines increase the production of controlled fire line, while firefighter crews do not tend to contribute to controlled fire line production. Production of controlled fire line is more efficient if it occurs along natural or built breaks, such as rivers and roads, and within areas previously burned by wildfires. However, results also indicate that productivity and efficiency of the controlled fire line are sensitive to weather, landscape and fire characteristics.

1. Introduction

Public agencies from around the world devote substantial resources to manage and respond to natural hazard events and disturbances, such as floods, hurricanes, earthquakes, the spread of invasive species, and wildland fires. For example, expenditures on wildfire suppression by the U.S. Forest Service (USFS), the federal agency with the greatest responsibility for wildland fire management, totaled about $10.2 billion (in 2012 dollars) over the decade ending in 2012. However, little is known about the productivity and efficiency of natural hazard management by public agencies or how control efforts affect the risks posed by natural hazards. In this paper we model the production of effective wildfire containment using Stochastic Frontier Analysis (SFA), and examine the determinants of estimated inefficiencies in containment production.

Wildland fire management provides an interesting setting for studying the productivity and efficiency of public agency responses to natural hazards. Thousands of wildfires occur each year within the United States, and increases in federal spending on large wildfire management has become a growing concern to Congress, state and federal agencies, and the public (Butry, 2009; Calkin et al., 2005; Gebert et al., 2007; Hesseln et al., 2010). Wildland fire management also fits within a broader class of hazard control problems that are characterized by spatio-temporal processes and a potential role for public management, such as biological invasions and public health epidemics (Epanchin-Niell and Wilen, 2012).

Suppression of large wildfires (greater than 121 ha) is a major component of wildfire management program. Less than 2 percent of wildfires escape initial containment efforts and become large fires, but these escaped fires account for 95% of total hectares burned and 85% of the total suppression expenditures (Donovan and Brown, 2005). Large fires are different than small fires in that these fires exhibit intense fire behavior and faster growth rate. When an ignition is identified, initial attack (IA) suppression resources are dispatched to immediately extinguish the fire using direct attack tactics. Once dispatched resources arrive on the fire, they build fireline around the growing fire perimeter. Once total suppression resource production exceeds the total perimeter of the growing fire, the fire is successfully contained. If the fire growth rate exceeds suppression

* Corresponding author.
E-mail address: hari.katuwal@umontana.edu (H. Katuwal).

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capacity the fire is declared escaped and typically a larger management team will be assigned to the event. Several IA models have been developed to support creation of dispatch rules for field application (Arienti et al., 2006; Fried and Fried, 1996; Ntaimo et al., 2013; Wei et al., 2015).

Large fire management is considerably more complex than initial attack of small fires. The increased size and more severe wildfire behavior that led to escape frequently requires a range of strategic objectives and tactical approaches. For large fires, line construction generally occurs simultaneously along multiple sectors, frequently involves construction of indirect line at a distance from the active fire edge, and may be accompanied by burnout operations (Finney et al., 2009). The efficiency and effectiveness of efforts to suppress large wildfires is not yet well understood (Butry et al., 2008; Finney et al., 2009; Holmes and Calkin, 2013), and it is not yet known how managers can improve operational efficiency of large wildland firefighting to reduce suppression costs or improve other outcomes (Holmes and Calkin, 2013).

The production of fireline to contain fire growth has been an important component of studies of optimal large fire management and suppression models.[1] Models of optimal suppression efforts have specified the production of stochastic fireline width that influences the likelihood of line containing fire growth (Mees and Strauss, 1992; Mees et al., 1994). The construction rates of fireline may be affected by a variety of conditions (Fried and Gilless, 1989), and variable construction rates play a role in determining the effectiveness of suppression efforts for containing fire size (Podur and Martell, 2007). However, few studies take an empirical approach to understanding the effectiveness of suppression resources for containing large fires.

Understanding the production and efficiency of wildfire suppression effort can help decision makers better allocate suppression resources to achieve fire containment objectives. After a fire has ignited, under-allocating resources for suppression may compromise efforts to minimize potential damages and costs associated with a large wildfire; conversely, over-allocating resources can increase costs and the exposure of personnel to risk and may tie up resources that could be productively used on other incidents. Results from the SFA model of wildfire containment could indicate the relative productivity of inputs used in suppression activities and identify conditions and characteristics of efficient suppression efforts.

The paper is organized as follows. Fire line productivity and effectiveness is discussed in the next section followed by theoretical background on stochastic frontier models. We describe the collection and interpretation of the data in Section 4 followed by the model results in Section 5. Conclusions and potential future research are presented in the last section.

2. Suppression effectiveness for large wildfires

Estimating production and efficiency relationships for wildfire management requires an understanding of the objectives and output of wildfire suppression efforts, which are complex and difficult to define and measure. The relevant measure of output may vary between fires and depend on several other factors associated with fire, landscape, and socio-political characteristics (Holmes and Calkin, 2013; Mendes, 2010; Plucinski et al., 2012). Measures of suppression effectiveness used in the past include the construction of fire line per unit time (i.e., a physical barrier to contain the spread of fire), success of initial attack (IA) (defined as the containment of a new ignition within about one day), area burned or protected, time until fire containment, and the probability of containment (Butry, 2009; Finney et al., 2009; Holmes and Calkin, 2013; Mendes, 2010; Plucinski, 2012).

For a majority of large fires, the objective is to limit the potential damage caused by the fire by containing and extinguishing it as quickly as possible. Thus, production of controlled fire line is a common objective for large wildfire suppression effort. Fire lines are constructed around the perimeter of the expected fire area to stop fire from spreading further. The objective of constructing fire line is to cut off the supply of fuel and stop the fire from spreading. Fire lines are made by cutting, scraping or digging with hand tools and/or other mechanized equipment such as bulldozers. Additionally, water or aerially delivered fire suppressants and retardant may be used to suppress fire perimeter and in some cases fire is intentionally used to burn out fuels in advance of a spreading wildfire to reduce available fuels and improve the likelihood that constructed fire line is not breached (Finney et al., 2009; Plucinski and Pastor, 2013).

Studies of suppression productivity and efficiency that use a production function approach have defined suppression output in various ways. Mendes (2010) suggests defining output as the number of burning hectares extinguished per unit time in a general microeconomic production model of wildfire suppression strategies. Hesseln et al. (2010) define the suppression objective as the minimization of economic losses, and the output of the suppression production process is defined as “avoided losses”. This approach requires a subjective estimate of the losses that would have occurred had the fire not been suppressed, a highly complex undertaking. More relevant to this study, Holmes and Calkin (2013) used a Cobb–Douglas production function to estimate the production of contained fire line for large fire suppression.

The definition of fire line as the output of the suppression production process is convenient because it is a readily observable (with appropriate data) and the factors of production are known and often can be observed constructing fire line. A few studies have investigated fire line production rates. Observations of fire line construction have been used to develop standard line-building rates used as a reference guide by fire managers (Broyles, 2011). Whereas, Hirsch et al. (2004) used data obtained from expert judgment to estimate production rates for a subset of suppression resources. However, data to understand the complex interaction of constructed fire line with an actively spreading large wildfire are not systematically collected for wildfires within the US. Holmes and Calkin (2013) used daily reports of percentage contained and area burned to calculate fire line output, and noted that collection of more accurate operational data could help identify the important factors that contribute to productivity and inefficiency.

Accurate measurement of the fire perimeter's progression has been a barrier to estimating the production of fire line and efficiency of suppression efforts. In this study, detailed geospatial data on the progression of fires provide an opportunity to overcome this difficulty. Similar to Holmes and Calkin (2013), we assume that the objective of large fire suppression efforts is to arrest the growth of fires using fire line to contain their spread. The output associated with this objective is controlled fire line, defined as perimeter segments that did not burn over at a later time. Observations of daily fire perimeters over the course of a fire are used to identify those perimeter segments that succeeded in containing the fire (i.e., they did not burn over at a later time). In a production framework, daily observations of controlled fire line are associated with suppression inputs that can be used to construct fire line and other factors that may affect the production or efficiency of the suppression effort.

[1] Thanks to an anonymous reviewer for pointing this out.