Effect of Slope and Packing Ratio on the Behavior of Matchsticks Burnings

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Abstract

The experiment was conducted to demonstrate the behavior of fire propagation on wildland using matchsticks forest model. A model forest was designed on a flame resistance clay, on top of which matchsticks were inserted and kept vertical to the ground by keeping spacing between them constant with the help of aluminum grid. The data for distance traveled by fire with time was taken at wide range of slopes from downhill of -25^o to uphill of 45^o on model forests of packing ratios of 0.08 and 0.04. The minimum rate of fire spread was observed around 15^o downhill. The data collected from this experiment follows nature of $tan^2\theta$ and agrees with Rothermel mathematical model of fire propagation except at high elevation above 35^o for low packing ratio.

Introduction

Wildfire is a natural periodic event that cleans up the wild vegetation and is necessary for soil fertilization [1]. However, these fires become devastating in many occasions and cause tremendous losses every year. A faster deforestation, uncompensated environmental loss, and economical impairment are some of their impacts in the society. Understanding the behavior of wildfire propagation would help people to effectively supply humanitarian aid in affected areas and would also help in modern forest plantation. Many studies have been conducted in past to predict wildfire propagation and to protect wildland from fire damage [2–5]. Some of these reports state that slope has relatively low effect in the absence of wind on fire spread [6], slope can significantly affect the rate of fire spread [3], average size of flame increases with the slope [3], and rate of fire spread follows $tan^2(slope\ angle)$ if there is no wind [5]. These studies, however, have put light on many important aspects of fire propagation, yet more investigation is needed to clearly understand such a complicated phenomenon.

In this study, we aim to further investigate and understand the fire propagation in forest by designing sets of experiment with matchsticks forest model at different slopes and packing ratios. Two sets of experiment were designed to measure the rate of fire spread on matchsticks fuel bed ranging from slopes of -25^o to 45^o with packing ratios of 0.08 and 0.04. All tests were conducted in an open space with temporary side walls to block any wind, and were maintained at $58^oF \pm 3$ of ambient temperature, $\sim 76\% \pm 4$ relative humidity, and at still wind velocity. Arrays of protruding matchsticks on clay were used to investigate the behavior of fire spread based on fuel sticks spacing and the fuel bed elevations. Flame length, headfire and backfire speeds were also considered to predict fire propagation behavior. Some of the outliers, which may be assumed to be more influential in data because of backfire and headfire behavior were removed from the data table to predict alternate curve fitting after analyzing the data by Cook's distance plot with the help of CRAN R software. However, both the curves (before and after removal of data points) are shown in results & discussion section. Since the experiments were conducted only in a laboratory based setup at still wind, these data may or may not predict the ground reality of forest fire behavior.

Materials and Methods

Two sets of experiment were conducted on a heat resistance clay as a fuel bed and kitchen matchsticks as fuel. The uniformity of matchsticks fuel size was not verified in this experiment. Matchsticks were arranged in a regular array of 9cm by 5 cm fuel bed. The gap between sticks were 0.50 cm and 0.82 cm apart in set I and set II experiments respectively. Matchsticks were inserted on the clay bed in such a way that they were vertical to the ground irrespective of the slope. Aluminum grids were used to make equidistant holes on the grid. Grid I consisted of holes of 0.24 cm at 0.50 cm apart, and grid II consisted of holes of 0.24 cm at 0.82 cm apart. An inclined plane was used to elevate fuel bed to different slopes to replicate hills. Precautions were taken to maintain the gap between the sticks when arranged on the fuel bed. Each set of experiment was performed on the same fuel bed. The thickness fuel bed was 0.50 cm. The wind velocity and ambient temperature reading was taken by an anemometer HP866B. However, experiments were conducted only in absence of wind velocity. Packing ratio, the ratio of volume of fuel to the volume of fuel bed including sticks is maintained at 0.08 and 0.04 in set I and set II experiments respectively. One experiment was also performed on 0.02 ratio but almost no fire spread was recorded on zero level bed. One extra matchstick was inserted on fuel bed at middle of the first row to ignite the matchsticks fuel. Flame height, headfire, and backfire speed (not presented here) were also considered to understand a behavior of fire spread.

Videos of burning matchsticks on fuel bed were taken at slow motion mode of 120 frame per second with the help of iPhone 6s camera. For easy understanding of fire propagation, we have expressed the fire speed in an arbitrary unit (au) rather than m/s. Rate of fire spread was recorded using the Tracker, a Video Analysis and Modeling tool software. Figures (1a), (1b), (1c), and (1d) shown below are an experimental setup of fuel bed before, during, and after fuel burnings. In figure (1d) the vertical line represents the height of flame. All experiments were conducted in an open atmosphere at $\sim 58^o F \pm 3$ of ambient temperature, $\sim 76\% \pm 4$ relative humidity, and no wind velocity.

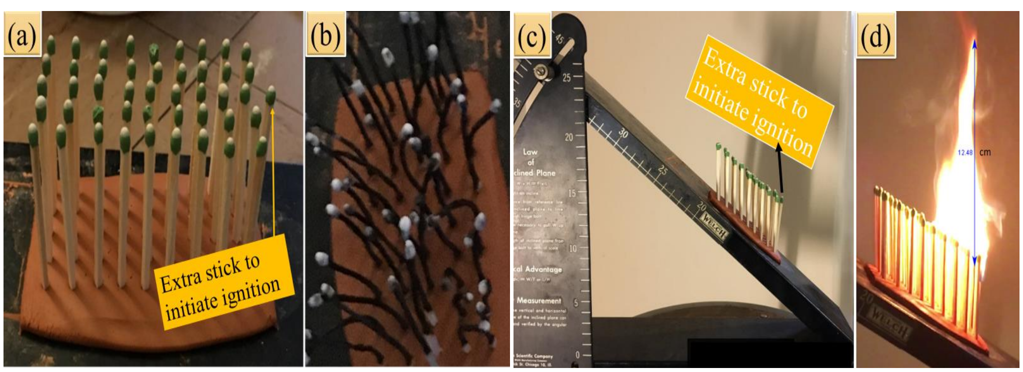

Fig 1. Experimental Setup. Figures (1a), (1b), (1c), and (1d) represent experimental setup for matchsticks inserted on a clay bed, curled up burnt sticks, fuel bed at 40^o slope, and burning sticks respectively.

Results & Discussion

Figure (2a) is the data generated by a Tracker as the distance travelled by fire progressing with time along the x-axis on fuel bed, and figure (2b) is a line of best fit to determine the rate of fire spread on two of experimental data. We used a R software to analyse the data once the data was generated from Tracker. The equation of line of best fit in figure (2b) is $y = a + bx$, where $b = 14.71 \pm 0.29$, and $a = 0.31 \pm 1.2$ for the red line (I),and $b = 7.65 \pm 0.08$, and $a = -22.69 \pm 0.94$, for the black line (II) with the coefficient of determination 99% for both lines. Hence, the rate of fire spread was 14.71 ± 0.29 for slope at 40^o and 7.65 ± 0.08 for that at -10^o.

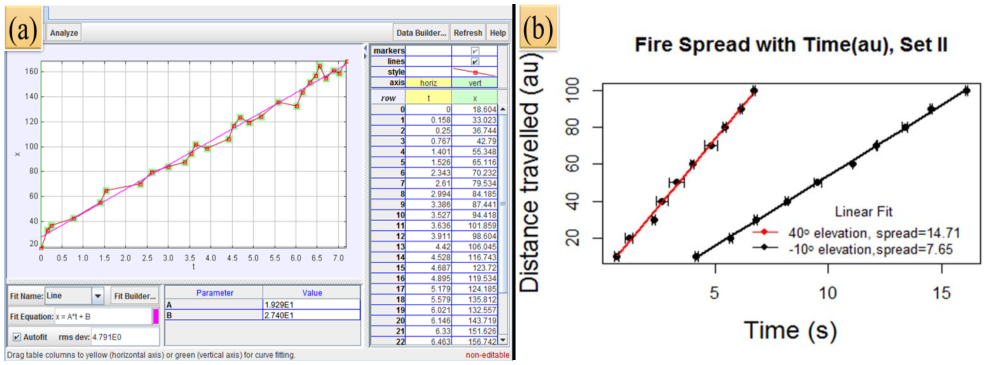

Fig 2. Data generation by Tracker tool as fire travels along the x axis with time, figure (2a), Line of best fit for distance travelled by fire with time at uphill 40^o, and at downhill -10^o, figure (2b).

Figures (3a) and (5a) represent curve fittings on raw data for rate of fire spread with elevation. The equation of curve fittings is given as $y = a + bx + cx^2 + dx^3$, where the coefficients of polynomial are $a = 12.7 \pm 1.3, b = 0.01, c = -0.002$, and $d = 0.00006$ in figure (3a), $a = 9.33 \pm 0.7, b = 0.1, c = 0.001$, and $d = -0.00001$ in figure (5a). Nature of curve in figure (3a) indicates that rate of fire spread remains almost constant from slope zero to 15^o uphill elevation, increases slowly as elevation increases thereafter, and decreases for downhill as steepness increases. The curve in figure (5a) represents that the rate of fire spread increases almost linearly with the uphill slope and decreases linearly as slope of downhill increases. Such results do not agree with the mathematical model of Rothermel [5]. However, we observed through Tracker that the fire propagation was slow initially as downslope increases, but became faster after burning of couple of rows. So, we decided to analyze our data to locate and remove outliers using Cook's distance plot figures (3b) and (5b), and found that there were two high influential points in data set I and one point in data set II. Figures (4a) and (6a) represent the curve fittings after removal of outliers from our data set I and II respectively. These curves agree with Rothermel model of $a(1+b.tan^2\theta)$ where $a = 10.47 \pm 0.3, b = 0.03 \pm 0.01$ chosen from curve fitting of figure (4a), and $a = 8.3 \pm 0.3, b = 0.03 \pm 0.02$ chosen from curve fitting of figure (6a). For comparison purposes, we have shown our experimental data as blue and red curves together with mathematical model $a(1 + b.tan\theta)$ and $a(1 + b.tan^2\theta)$ curves as green and black lines in figures (4b) and (6b). The shaded region around curves are standard error in figures (4b) and (6b). We did not find any portion of our data that matches with $a(1 + b.tan\theta)$. In figure (6b) spread grows rapidly as the slope increases and then slows down at higher elevation above 35^o. This slowdown may be due to the increment in height difference between fuel materials at low packing ratio. Such effect was not observed for high packing ratio of 0.08, which may be due to backfire and headfire length that help spread fire rapidly in shorter fuel distances.

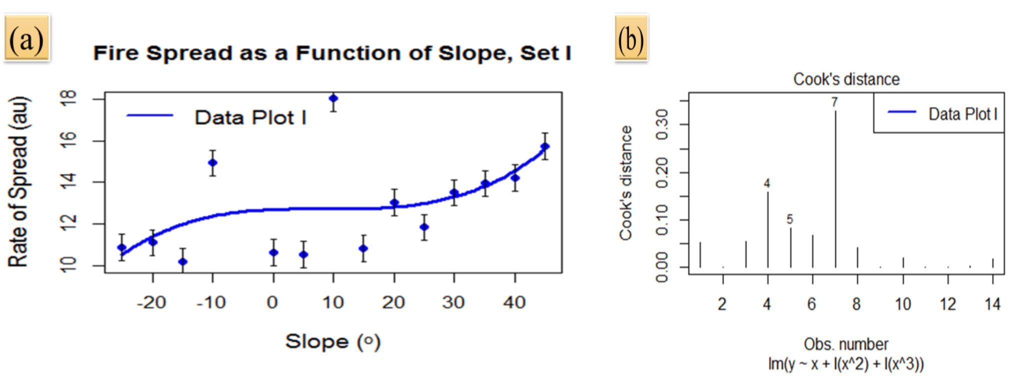

Fig 3. Curve fitting on raw data of set I experiment, figure (3a); The equation of curve fitting is given as $y = a + bx + cx^2 + dx^3$, where a = 12.7, b = 0.01, c = -0.002, and d = 0.00006. Cook's distance plot for this data to find high influential points that effect the curve shape, figure (3b).

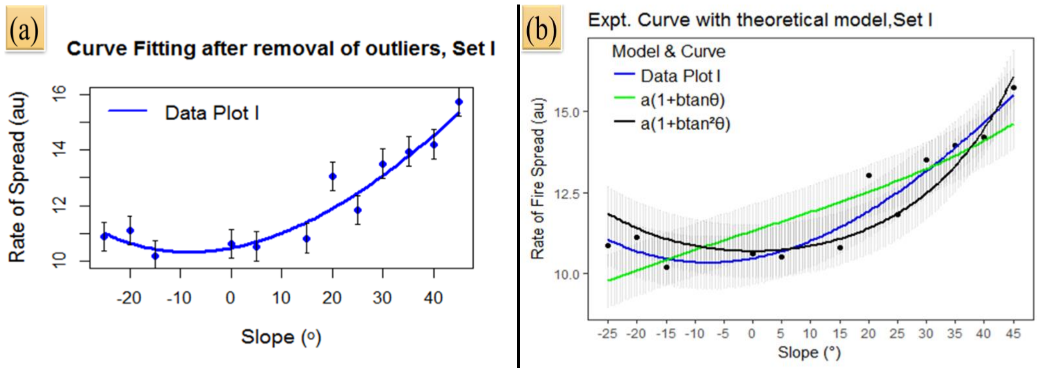

Fig 4. Curve fitting after removal of high influential points from data set I, The equation of curve fitting is given as $y = a + bx + cx^2 + dx^3$, where $a = 10.47$, $b = 0.03$, $c = 0.002$, and $d = -0.000008$, figure (4a); Comparing the nature of set I data with theoretical models, figure (4b).

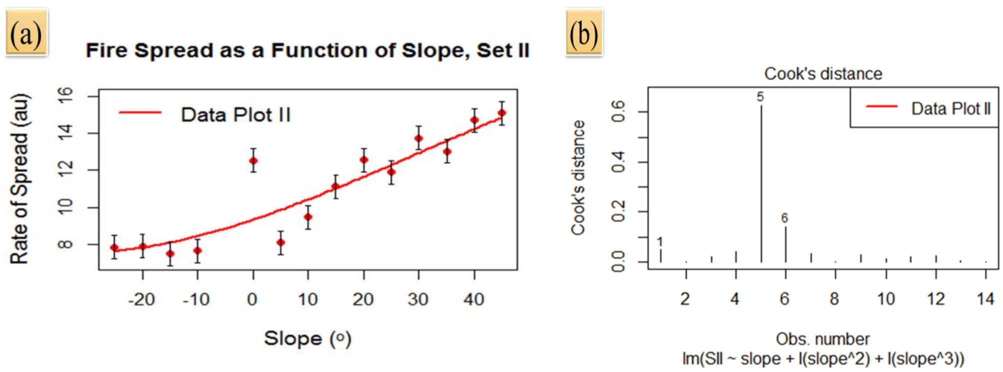

Fig 5. Curve fitting on raw data of set II experiment. The equation of curve fitting is given as $y = a + bx + cx^2 + dx^3$, where a = 9.33, b = 0.1, c = 0.001, and d = -0.00001, figure (5a); Cook's distance plot for set II data to find high influential points that effect the curve shape, figure (5b).

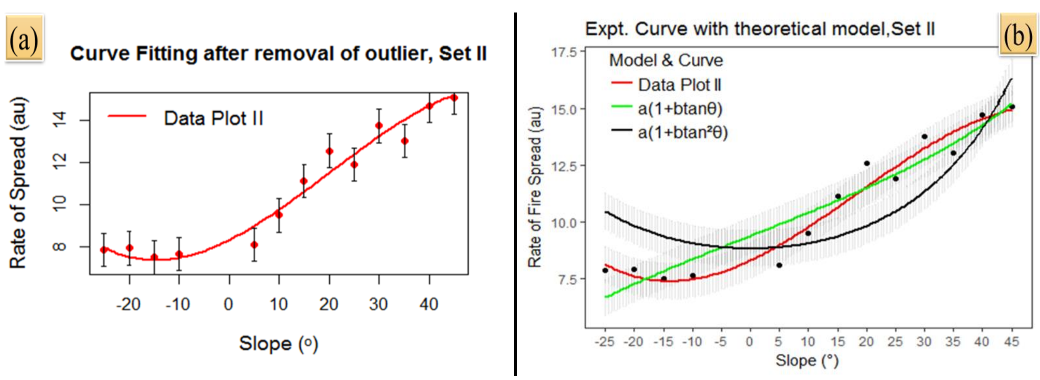

Fig 6. Curve fitting after removal of high influential point from set II data, The equation of curve is given as $y = a + bx + cx^2 + dx^3$, where a = 8.29, b = 0.1, c = 0.003, and d = -0.00005, figure (6a); Comparing the nature of set I data with theoretical models, figure (6b).

Conclusion

In this experiment, we studied a behavior of fire propagation on uphill and downhill forest by designing a clay fuel bed inserted with matchsticks. Two different packing ratios of matchsticks fuel beds were included in this experiment. Our data follows the pattern of $tan^2\theta$ model as predicted by Rothermel [5] except at high elevation for low packing ratio. At low packing ratio our data indicates the rate of fire propagation slows down with higher slope of more than 35^o. However, at high packing ratio the rate of fire spread increases with the increase of upslope and is proportional to $tan^2\theta$. The minimum rate of fire spread was observed around 15^o downslope.

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