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A computational study of the interactions of three adjacent burning shrubs subjected to wind

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ABSTRACT

A three-dimensional physics-based model was used to investigate the effect of shrub size, shrub separation distance and wind on the burnout times of shrubs. The shrub considered for this study was chamise. Two shrub sizes with different physical dimensions and initial masses with two wind speeds were considered. The study was performed for an array of three shrubs with separation distances ranging from zero to one shrub diameter. The shrubs were situated at the vertices of an equilateral triangle with two shrubs placed upwind (upstream shrubs) of the third shrub (downstream shrub). For a smaller shrub and a higher wind speed, the direction of fire front propagation within the shrub was found to be opposite to the direction of the wind, which resulted in a longer burning time for the shrub. For larger shrubs, a decrease in burning time was observed with an increase in wind speed. The burnout time for upstream shrubs increased with an increase in shrub separation distance for all shrub sizes and wind speeds considered. The burnout time for the downstream shrub was found to decrease with an increase in the separation distance, reach a minimum, and then increase with an increase in separation distance. The trends observed in burnout times for downstream shrub were attributed to the balance between heat feedback into the downstream shrub from the flames in upstream shrubs and availability of sufficient oxygen for combustion to take place.

1. Introduction

Wildland fire propagation is impacted by several factors such as atmospheric conditions, vegetation density, moisture content of vegetation and presence of nearby fire sources. Two of the most important factors include the presence of nearby fire sources and the presence of ambient wind. When separate fires are placed in closed proximity to each other, they interact and converge in one location and ultimately behave like a single large or mass fire [1]. Under windy conditions, it is known that the rate of spread of fire increases compared to cases with no wind [2,3].

A theoretical analysis of flame interactions was performed by Thomas et al. [4] where they proposed a functional relationship between the length of merged flames, separation distance and characteristic dimensions of the burners. They theorized that when two flames are placed in close proximity, a pressure drop is created between the neighboring flames as a result of a restriction in air entrainment. The flames are thus deflected from the vertical, with the greatest deflection occurring in the region of maximum pressure drop. A functional relationship between merged flame height, dimensions of fire source, and the separation distance between the fire sources was proposed using Bernoulli's equation and assuming, that the rate of air entrainment is unaffected by pressure gradients induced due to flame merging. Theoretical predictions of flame height were compared with experimental measurements using 60 cm×30 cm and 30 cm×30 cm burners supplied with methane gas. Merged flame height measurements from experiments and theory were in good agreement when the separation distance between the burners was small.

While, Thomas et al. [4] performed a theoretical analysis for two fuel beds, Baldwin [5] extended the theory to include a square matrix of n^2 fires from data obtained through experiments with porous burners using natural gas as the fuel. The experimental approach consisted of square array configurations varying from two to sixteen burners and burner sizes of 1 ft. ×1 ft. and 2 ft. ×1 ft. The theoretically derived scaling law between merged flame heights and separation distances between fire sources predicted the onset of flame merging, i.e., an increase in flame heights, with appreciable accuracy, and were independent of the number of fires involved. Subsequently, numerous works have examined flame merging in either pool fires [6–9] or on flames over porous burners [10,11], finding a strong correlation between fuel spacing and burning rate of individual fires. They have reported that as the fuel spacing increased, the burning rate increased

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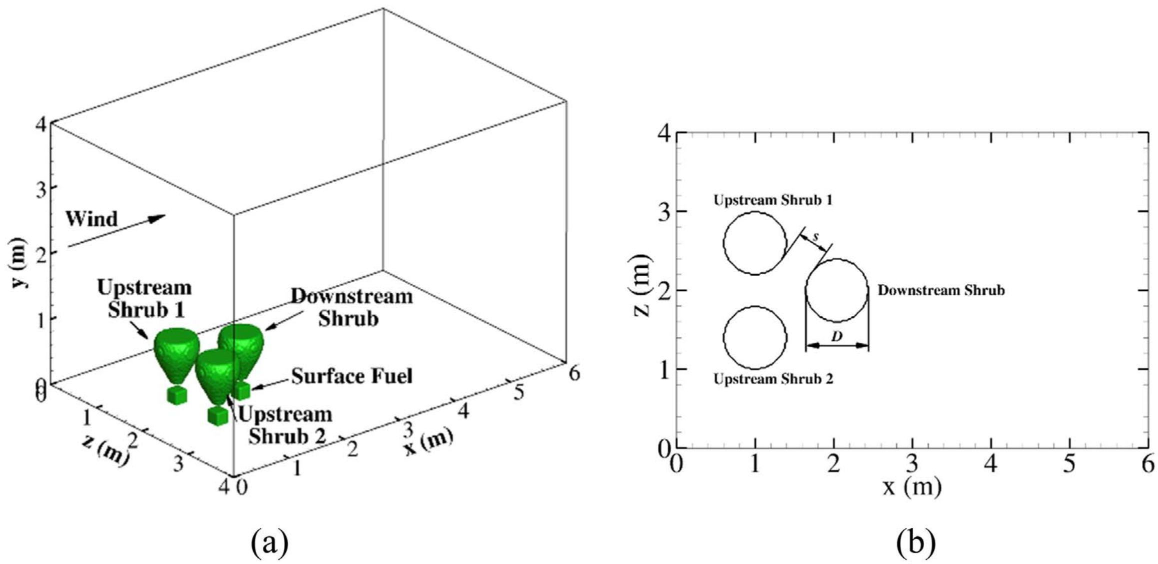

Fig. 1. Schematic representation of computational domain. (a) Shrub arrangement; (b) Definition of shrub separation distance (s/D).

to reach a maximum, and then decreased with a further increase in fuel spacing.

In a series of papers, Liu et al. [7–9] investigated flame interaction and flame merging phenomena in square fire arrays. The experiments were performed with square fire arrays consisting of multiple equidistant fires from fuel pans of *n*-heptane. The various arrays considered ranged from 3×3 to 15×15, with the fire spacing ranging from 5 to 50 cm. They used burnout time for the individual fuel sources with respect to a global burnout time, and flame heights to quantify flame merging. Their analysis showed the presence of two competing fire interaction mechanisms: heat feedback enhancement and air entrainment restriction. When the distance between the fire sources was less than a critical separation distance, the effect of heat feedback enhancement dominated air entrainment restriction. When the fire spacing was increased air entrainment mechanism dominated the heat feedback mechanism.

In the context of wildland fires, Dahale et al. [12] used a physics-based model [13] to study fire interactions in chamise shrubs. They studied fire interactions in two- and three-shrub arrangements in the absence of crosswind. The shrub used in the study was 0.6 m in diameter and 1 m in height with an initial mass of approximately 0.6 kg. Fire behavior was described in terms of global parameters such as shrub mass loss rates and total heat release rates, as well as local parameters such as the temporal evolution of temperature at points of interest within the shrub. It was found that the maximum rate of consumption of shrub mass and fire spread along the shrub height decreased as shrub separation distance increased. Flame heights from three-shrub arrangements were reported to be significantly higher than two-shrub arrangement suggesting stronger fire interactions in the former. It is noted that previous works that used physics-based modeling to investigate shrub or shrub-like canopy crown fires are due to Overholt et al. [14,15] who modeled the burning of isolated little bluestem grass, and Dahale et al. [13] and Padhi et al. [16] who modeled the burning of isolated chamise shrubs.

The presence of ambient wind results in higher fire spread rates compared to cases with no ambient wind. If the wind is in the direction of fire propagation, resulting in a 'heading fire', the flame tilt angle, measured from the vertical, between the fire front and the surface fuel can increase, resulting in an enhancement of radiation and convection heat transfer to the unburned surface fuel ahead of the fire front. The result is an increase in burning rate, higher flow velocities, increased flame heights, and increased rate of spread and higher burning intensity. If the wind is in a direction opposite to that of fire propagation, resulting in a 'backing fire', the flame will tilt away from the unburned fuel. Thus, the unburned surface fuel ahead of the fire front receives less radiation and convection heat from the flames leading to a decrease in burning rate and the overall rate of spread [17].

Although there has been extensive study on burning rate measurements due to flame interaction for various liquid fuel pools with different pool diameters and flames from porous gas burners, studies on burning rates in shrub fires is lacking. Wildland fuel is characterized by small, discrete particles, such as leaves, branches and other wood particles, which are discrete compared with pools of liquid fuel, and highly porous compared with porous burners. Thus, it is important to understand the effects of wind, fuel spacing and size of fuel matrix in vegetative fuels to perform safe and successful prescribed burns.

Thus, the objective in this paper is to study the effect of shrub separation distance, size of shrub and wind on the burning time of shrubs. A physics-based continuum model [13] is used, wherein governing equations for the various thermo-physical phenomena involved in fire spread through vegetative fuels are solved numerically. The next section provides a description of the problem statement followed by a summary of the physics-based model used in this work.

2. Problem setup and computational methodology

A schematic of the computational domain used in this work is shown in Fig. 1(a). The shrub arrangement was chosen such that each shrub is placed on the vertex of an equilateral triangle as shown in Fig. 1(b). The crown separation distance is defined as the distance between the inner edges of the shrubs, which is indicated by s, normalized by the maximum value of the shrub diameter D along its height. Five normalized separation distances, s/D =0.0, 0.25, 0.50, 0.75, and 1.00, two wind speeds U_∞ =1 and 2 m/s, and two shrub sizes were considered. The smaller shrub is 1 m tall with a maximum diameter of 0.6 m and 0.57 kg in mass. The larger shrub is 1.2 m tall with a maximum diameter of 0.8 m along its height and 1.15 kg in mass. Also, the diameter of the base of shrubs is 0.1 m for smaller shrubs and 0.2 m for larger shrubs. In addition, simulations for burning of an isolated shrub with two shrub sizes and wind speeds mentioned above, were also performed to understand the impact of neighboring fires on the burning of individual shrubs.

In each case, the crown fuel was chamise (*Adenostoma fasciculatum*). The crown was assumed as a porous medium comprising of two distinct components: branches and foliage, with a mass-based proportion fixed at 53% and 47%, respectively. This choice was guided by the