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Experimental study and large eddy simulation of effect of terrain slope on marginal burning in shrub fuel beds

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Abstract

This paper presents a combined study of laboratory scale fire spread experiments and a three-dimensional large eddy simulation (LES) to analyze the effect of terrain slope on marginal burning behavior in live chaparral shrub fuel beds. Line fire was initiated in single species fuel beds of four common chaparral plants under various fuel bed configurations and ambient conditions. An LES approach was developed to model fire spreading through a fuel bed with a subgrid scale turbulent combustion model based on a flame surface density concept. By examining two fuel bed slope configurations, it was found that upslope fire spread depends not only on the increased radiant heat transfer but also on the aerodynamic effect created by the interaction of the flame with the inclined surface. Under certain conditions, the convective heat transfer induced by this interaction becomes the dominant mechanism in determining fire spread success. Seventy-three (or 42%) of 173 experimental fires successfully propagated for slopes ranging from −70% to 70%. It was found there exists a critical slope above which fire spread in these live fuel beds was successful, and below which fire spread was unsuccessful. This critical slope for marginal burning varied widely with fuel moisture content and fuel loading. A stepwise logistic regression model was developed from experimental data to predict the probability of successful fire spread. It is expected that this model may be helpful in providing guidelines for prescribed fire application.

Keywords: Marginal burning; LES; Slope; Chaparral; Flame spread

1. Introduction

Wildland fire commonly occurs in Mediterranean climates that are characterized by cool, moist winters and hot, dry summers [1]. Fuel complexes of various shrub species prevalent in these areas exhibit significant fire behavior. The shrub complexes are known by various names such as fynbos (South Africa), mattoral (Chile), garrigue (France), and chaparral (California, US). Approximately 85% of the vegetation area burnt during the 2003 fires in southern California was in chaparral, indicating the importance of managing chaparral vegetation. Prescribed fire is one of the alternative strategies used by land management agencies to reduce wildland fuels and prevent wildfires [2]. Because of the fire risk in

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chaparral and other living fuels, prescribed fires are often conducted under marginal burning conditions. These conditions occur when environmental variables such as wind speed and direction, air temperature, relative humidity, and topography, and fuel conditions such as type, moisture content, and continuity result in low-intensity fire that may or may not spread successfully. However, even when all variables are seemingly within the prescribed conditions, often ignition results in little, or no fire spread, due to undesired extinction. Consequently, the cost of prescribed burning increases as significant equipment and personnel allocation costs are incurred prior to ignition. It is thus desirable from both an economic and scientific perspective to gain a better understanding of marginal burning conditions.

Chaparral grows extensively on hilly terrain, indicating the importance of understanding marginal burning in live fuels occurring on flat and sloped (up and down) terrains. The literature review reveals that only a limited number of experimental studies have investigated slope effects in dead fuels and virtually none have studied wildfire spread in live fuels under marginal burning conditions [3–9]; most of our previous laboratory experiments were limited to zero slope conditions [10,11]. Towards this end, a dual approach including experimental and numerical modeling was adopted to study the effect of terrain slope on marginal burning.

Over the last forty years, a significant amount of interest in numerical modeling of wildland fire spread has been generated within the scientific community. Operational models [12–14] refer to computer-based, semi-empirical models that are currently utilized in the field for decision support systems. They do not include a two-way coupling between the fire and the fire-induced fluid flow in the atmosphere. Furthermore, they were designed primarily for dead, not live, fuels. Coupled atmosphere-fire research models [15–18] on the other hand focus on improved methodologies, often limited in scope and designed to better understand specific physical processes. Research models for fire spread at intermediate length scales (typically laboratory scale fire spread experiments through fuel samples) have included simple gas-phase turbulent combustion models and an appropriate form of the Reynolds-averaged Navier Stokes (RANS) equations, including transport equations for gaseous chemical species arising through pyrolysis of solid fuel [19–22]. These research models are appropriate to overall length scales of the order of a few meters.

In this paper, a three-dimensional large eddy simulation (LES) approach to model a fire spreading through a fuel bed is developed. In LES, the super-grid scales are accurately resolved, while the subgrid scales (SGS) are modeled through appropriate closure models. A recently proposed SGS turbulent combustion model, based on the well-known concept of flame surface density, was applied to model finite rate chemistry effects [23]. This LES approach is motivated by our desire to develop a physically more accurate method to simulate fire spread through a porous shrub fuel bed, compared to previous approaches [20,22]. When fire spreads upslope, it is observed that propagation depends not only on the increased radiant heat transfer rate [24–27], but it is also influenced by the complex aerodynamic flow created by the interaction of the flame with an inclined surface [28]. By obtaining instantaneous and detailed data on turbulent flow, heat transfer, and fuel combustion, LES is a promising tool to model this complex, dynamic two-way coupling between the fire and the fire-induced fluid flow. Given the obvious difficulty with large scale fire spread, the current LES is restricted to model fire spread through shrub fuels at laboratory scales.

2. Experimental setup

Fuel beds (2.0 m long and 1.0 m wide) were prepared with one of four live chaparral species: manzanita (*Arctostaphylos spp.*), chamise (*Adenostoma fasciculatum*), hoaryleaf ceanothus (*Ceanothus crassifolius*), and scrub oak (*Quercus berberidifolia*) that are typical of the chaparral found near Riverside, CA. Fuel was cut in the morning in the North Mountain Experimental area at an elevation of 1160 m, bagged, and transported to the laboratory. The test bed was prepared and ignited early in the afternoon of the same day to reduce moisture loss from the cut material. The shrub fuel bed holder was constructed with an aluminum frame, 2.12 m long, 1.1 m wide, and 0.4 m high, and placed on an experimental platform that is 6.2 m long, 2.4 m wide and 0.6 m high. The surface above the frame was covered by steel mesh with grid size 5×10 cm. A known mass of fuel (L, kg/m^2) made up of a single species with branches with diameter less than 6.3 mm and including foliage was spread uniformly on the mesh to the final fuel bed depth $\delta = 20$ cm (or $\delta = 40$ cm). Because the foliage and branches in most chaparral shrubs are elevated above the ground, the fuel bed was elevated 0.4 m (stem space) above the platform. Thus, air could be entrained from the bottom of the fuel bed into the flame zone. The first 50 cm length of the fuel bed was designated as the ignition zone. Between 300–400 g of excelsior and a small amount of isopropyl alcohol (C_3H_8O) were added uniformly in the ignition zone to initiate and sustain a line ignition. Air entrainment from the lateral sides of the fuel bed was prevented by metal sheeting. It was found that most of the experimental fires maintain a rectilinear shape, and reached a quasi steady state after approximately half of the total length of the fuel bed. From a marginal burning perspective, an experiment resulted in a successful fire spread if the live brush fuel ignited from the ignition zone and then propagated the remaining length of the fuel bed. The experiment was considered unsuccessful if the fire, once ignited, failed to propagate. All fire tests were video recorded by a digital video camcorder for post fire spread analysis.

The effect of slope was simulated by raising one side of the fuel bed assembly. The slope angle is the angle θ, between the fuel bed bottom plate and the horizontal plane. Topographic slope is defined as the ratio of vertical rise and horizontal distance expressed as a percentage: slope = 100 tan(θ). Positive slope indicates uphill fire spread; negative slope indicates downhill fire spread.

3. LES methodology applied to fire spread

In a LES, the instantaneous, time-dependent, three-dimensional governing transport equations for various field quantities such as density, velocity components, species mass fractions, etc. are spatially filtered using a characteristic filter-width Δ [23]. This results in a set of transport equations for the filtered or resolved field. They include new terms that characterize sub grid scale (SGS) phenomena, occurring at scales below Δ. These SGS terms are modeled in terms of resolved quantities, to ensure closure of the system of filtered transport equations. The filtered conservation equations are expressed as

$$\frac{\partial \bar{\rho}\tilde{\phi}}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_i\tilde{\phi}}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\Gamma_\phi \frac{\partial \tilde{\phi}}{\partial x_i}\right) + \frac{\partial M_i^\phi}{\partial x_i} + S_{\phi,sg} \quad (1)$$

where $\tilde{\phi}(x,t)$ stands for a filtered generic fluid property which represents density (ρ, in Eq. (1), in which case ϕ is unity), three velocity components (u_i), enthalpy (h), species mass fraction (Y_i of moisture, oxygen, carbon dioxide, and pyrolysis fuel gas), and soot volume fraction. The quantity Γ_ϕ is the molecular transport coefficient, and the fourth term M_i is the unresolved SGS convective fluxes of momentum, energy and species that need to be modeled. In this work, M_i is modeled via an eddy viscosity model in which the eddy viscosity coefficient is given by the generalized Smagorinsky formula [29]. In the case of fire spreading through a fuel bed, taking into account water vaporization, pyrolysis fuel gas release, combustion in the gas phase, and char combustion within the preheating and burning process, the last source term $S_{\phi,sg}$ of Eq. (1) represents the mass exchange between gas and solid phase for density, drag force for momentum, convective and radiative heat exchange of energy between the two phases, and physical and chemical source terms for species, respectively. Further details of modeling M_i and $S_{\phi,sg}$ can be found in references [22,23].

One major challenge in introducing LES to wildland fire is the proper modeling of the filtered reaction rate $\bar{\dot{\omega}}_\alpha$ of gas species α, where the computational mesh size is generally very large whereas the flame thickness is generally very thin (<1 mm) so that the detailed reaction structure cannot be resolved. Here, the filtered reaction rate $\bar{\dot{\omega}}_\alpha$ of species α is estimated as the product of the consumption rate per unit surface area $\dot{m}_\alpha$ and the filtered FSD $\bar{\Sigma}$ which is the flame surface area per unit volume, i.e., $\bar{\dot{\omega}}_\alpha(\mathbf{x},t) = \dot{m}_\alpha\bar{\Sigma}(\mathbf{x},t)$ [23]. This approach is attractive since it decouples the complex chemical problem ($\dot{m}_\alpha$) from the description of the turbulence combustion interaction ($\bar{\Sigma}$). For wildland fuels, the composition of the pyrolysis products is complicated and temperature dependent. To simplify the problem, the pyrolysis gas is modeled as a mixture of CO, CH_4, H_2, and CO_2 [30].

The governing equations of mass, momentum, energy, and species mass fractions were discretized in a three-dimensional (3D) Cartesian coordinate system. An explicit (quadratic upstream) third order accurate scheme in space and time, QUICKEST [31] was employed to numerically integrate the governing equations. Including the contributions from gas (CO_2 and H_2O), soot, and solid phases, a 3D Discrete Ordinates (DO) method [32] was developed to calculate the radiative heat transfer within the flame and solid fuel. A 3D computational domain 1.2 m long, 1.2 m high and 1.2 m wide with a uniform grid system of $62 \times 62 \times 62$ cells was designed. The computational time on a Unix workstation (CPU 2.0 GHz) was about three weeks for 2 min of simulated fire spread time. Given the current computational capability, the experimental geometrical domain was not fully modeled and the boundary of the computational domain was not extended too far away after examining the effect of numerical boundary conditions. The modeled fuel bed was shortened to 0.8 m allowing us to focus on the initial ignition and subsequent propagation.

The fuel properties of chamise measured by Countryman and Philpot [33] were used in computation. For two solid phases (foliage and small branch) considered in the model, they have different values of density (ρ_s, dry wood mass per unit green volume) and surface-to-volume ratio (σ_s): foliage has $\sigma_s = 3687\ m^{-1}$ and $\rho_s = 376\ kg/m^3$, and branch has $\sigma_s = 1308\ m^{-1}$ and $\rho_s = 744\ kg/m^3$. The fuel heat content is 20.1 MJ/kg and the moisture content (M) changes with season and environment. Ambient temperature (T_a) and relative humidity (RH) are known to play important roles on wildfire spread. These environmental effects were considered in the current model.

4. Results and discussion

4.1. Aerodynamic effect induced by fire and slope

Each test bed was placed on a large platform that is designed to tilt up to an angle of 45° (slope = 100%) to the horizontal to model a terrain slope. This configuration is designated setup A as illustrated in Fig. 1a and models the actual arrangement of wildland fuels in mountainous terrain. Because of safety concerns involving use of the large tilting platform, another slope setup B was designed to lift one side of the fuel bed to different angles (see Fig. 1b) while keeping the heavy platform horizontal. Setup B is significantly easier to arrange and is not representative of actual fuel arrangement; however, setup B led to unexpected, yet insightful experimental results. Using setup B and chamise as fuel, a series of experiments was completed for three slope levels: zero slope, 40% upslope ($\theta = 21.8°$), and 60% upslope ($\theta = 31°$). At zero slope, slope setups A and B are equivalent. Other experimental conditions were essentially unchanged. Each case was repeated two times and the experimental sequence was random.

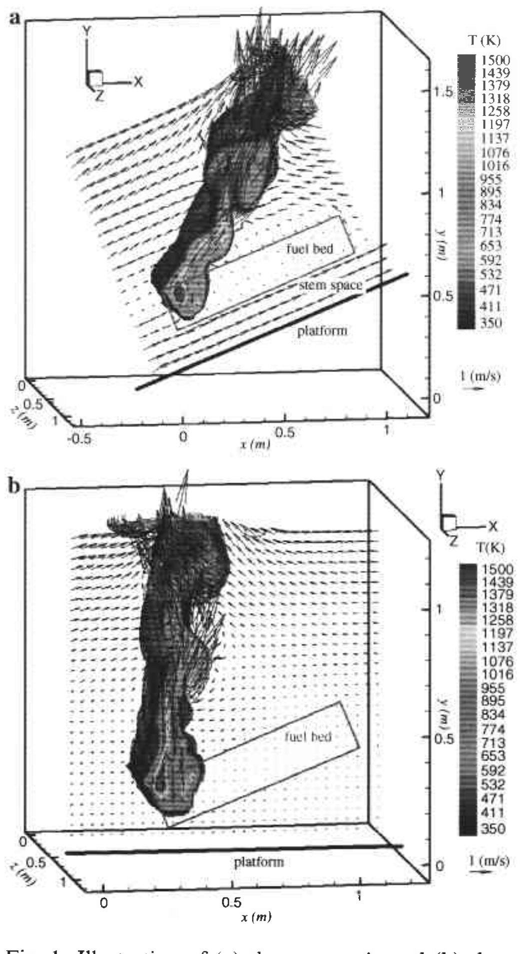

Fig. 1. Illustration of (a) slope setup A, and (b) slope setup B, with instantaneous 3D gas phase temperature contours in one half of the computational domain and a velocity vector field along the center section (x–y) calculated by LES at $t = 25$ s.

At zero slope setup, the fuel ignited from the burning zone and then propagated the length of the fuel bed. The fire spread rates approximated from video were 0.143 m/min and 0.171 m/min, respectively. For marginal burning analysis, these fire tests were described as successful. For other upslope fire spread cases with slope 40% and 60%, it was anticipated that fire would spread successfully and with faster spread rate in comparison with the zero slope case. However, experiments using setup B showed a contrary result that all fires did not spread, and extinguished within about 2 min after ignition. As analyzed by many researchers [24–27], upslope fires are closer to the unburned fuel, thereby increasing the radiation heat transfer rate incident on the fuel, the preheating rate, and thus the rate of spread. For slope setup B, these factors still affect the burning of chaparral fuel by increasing the radiative heat transfer to the fuel ahead of the flame front. However, this did not promote vigorous fire spread. In our limited marginal burning tests using setup A, it was found that the upslope conditions enhanced fire spread.

In wildland fire behavior studies, much attention is often devoted to radiation from the flame front as the dominating process in fire spread. Because of the complexity of turbulent flow induced in fire and modified by terrain, the role of convection for heat transfer is sometimes overlooked, making it difficult to explain some features that are observed in fire propagation in complex terrain, such as the above case. By comparing the fire behavior observed in experiments using setups A and B, it is seen that the main difference is due to the aerodynamic effect created by the inclined platform. The detailed flow field in the fire is currently unavailable because of our limited measurement capability. As an auxiliary research tool, the 3D LES approach was used to model chaparral fuel ignition process under the conditions close to experimental setups A and B as $\delta = 0.2$ m, $M = 50\%$, $L = 1.2$ kg/m^2, $T_a = 27$ °C, RH = 30%, and slope 40%. By analyzing the numerical results for flow velocities, temperature, and heat transfer, it is possible to understand the aerodynamic effect induced by fire and terrain slope on marginal burning behavior.

At time $t = 25$ s, Figs. 1a and b display the instantaneous 3D gas phase temperature contours in one half of the computational domain for setups A and B, respectively. The velocity vectors in a vertical section (x–y) along the center of the fuel bed denote the direction and speed of fluid flow. A fire plume is formed above the ignition zone of the fuel bed, and large vortical structures appear at the center and the edge of the fire plume. Ambient air is entrained into the fire plume. Inside the plume the gas undergoes an upward acceleration and the maximum instantaneous vertical speed reaches 4.3 m/ s. Within the fuel bed the flow speed (<0.07 m/s) is strongly reduced due to drag force induced by shrub fuel. When the time evolution of temperature contours is examined, it shows a classic Rayleigh–Taylor instability in which large vortical structures are semi-periodically shed from the burning zone and rise above in the fire plume as coherent structures. The fire plume displays a strong pulsation in flame height. The fire puffing frequency approximated from numerical results is roughly 1.6 Hz that is very close to experimental observations. Because most of burning occurs in the large vortical structures, the pulsation of these structures is believed to play an important role in determining the rate of entrainment, heat transfer rate, and also in determining the flame geometry. In setup B (Fig. 1b), air is entrained from both upslope and downslope sides by passing through the bottom of the fuel bed before entering the fire plume. In this case, the air entrainment from both sides is almost balanced, and the fire plume is vertical. Beneath the burning zone, the velocity vectors show an opposed flow induced by the aspired air and the velocity magnitude is very small. For setup A (Fig. 1a), however, air entrainment into the fire plume from the upslope side is restricted by the inclined platform; entrainment from both sides is thus not balanced. Figure 1a shows most of vortical structures appear at the upslope side of the fire plume. By averaging temperature contours in time, it is found that the flame is tilted toward the fuel bed. Under the burning zone in the stem space, the velocity vectors show a local 'wind' that blows upslope at about 0.5 m/s. In our experiments using setup A, the local wind was observed by tracing smoke that moved upward along the inclined platform.

To identify aerodynamic effects induced by fire and slope on heat transfer processes, we evaluated the accumulated value of various heat transfer variables integrated through the burning time as $QA(t) = \int_0^t Q(t')\mathrm{d}t'$. Figure 2 illustrates the time evolution of solid phase temperature (T_s), and accumulated heat absorbed or released by solid particles through convective heat transfer between gas and solid (QA_{conv}) and radiative heat transfer ($QA_{\mathrm{rad},s}$). A solid particle requires sufficient energy from QA_{conv} and $QA_{\mathrm{rad},s}$ to reach its ignition temperature. For a solid particle located at the bottom of the fuel bed, Fig. 2 shows that in the

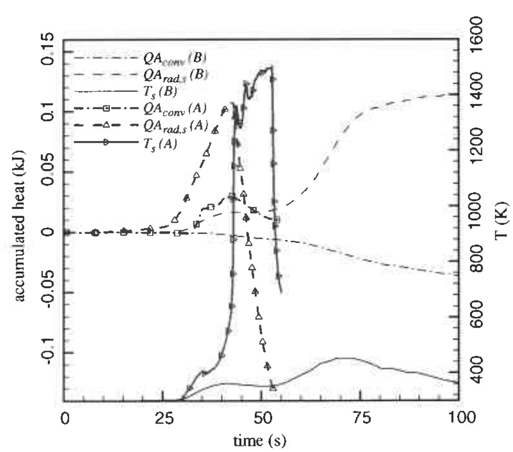

Fig. 2. Time evolution of solid phase temperature (T_s) and accumulated heat (QA_{conv} and $QA_{\mathrm{rad},s}$) absorbed or released by solid particle located at the bottom of the fuel bed for slope setups A and B.

case of setup A, it is ignited successfully due to increased energy from $QA_{\mathrm{rad},s}$ and QA_{conv}, however, in the case of setup B, it is not ignited because of the cooling effect (negative value) from QA_{conv} although $QA_{\mathrm{rad},s}$ is still strong. These calculations agree with the ignition results observed in experiments. The calculated fire spread rate for setup A was 0.42 m/min which is in the range of 0.23–0.44 m/min measured from repeated experiments.

The contrary results obtained from setups A and B demonstrate that the aerodynamic effect created by the interaction between the flame and the inclined platform became the dominant mechanism in determining burning success. Steeper the slope, the more rapidly the fire will burn upslope (and more intensely) because of both enhanced convective and radiative heat transfer rates. This was verified by our experimental results and by wildland fire behavior.

4.2. *Effect of slope on marginal burning*

To maintain the fire behavior of setup A, setup B was modified by attaching a piece of steel plate underneath the fuel bed, while maintaining the 0.4 m stem space between the bottom of the fuel bed and the steel plate. A series of fire spread experiments was completed using this modified setup. All experiments were conducted under no wind conditions. The natural changes in live fuel moisture content, ambient temperature, and relative humidity were considered by collecting fuels and conducting experiments over the course of an annual cycle (2003–2004). Moisture content (M) of hoaryleaf ceanothus samples burned on the day of collection was 68% on 11/18/2003, 88% on 5/17/2004, 61% on 7/9/2004, and 54%

on 9/10/2004, which indicated that new growth on May and drying out by September — a typical annual moisture trend in chaparral. Other fuels exhibited the change in moisture content similar to ceanothus. The dry fuel loading (L) was 1.2–4.9 kg/m^2 changed with depth ($\delta = 0.2$ m or $\delta = 0.4$ m) and fuel type. The environmental temperature (T_a) ranged from 16 to 39 °C, and the relative humidity (RH) ranged from 17% to 96%.

In the experiments, the slope percent was a static value that could be controlled accurately. Experimental uncertainties arise from the heterogeneous nature of the fuel samples and fuel bed, and variations in the ambient temperature, and relative humidity. Uncertainty would be reduced by averaging across repetitions for the same nominal values of all variables. Seventy-three (or 42%) of 173 tests resulted in successful fire spread for different slope percent, fuel moisture content, fuel loading, and ambient conditions. To quantify marginal burning, we define a "marginal burning index" (MBI) that is indicative of a fire's proximity to a successful spread. By excluding the ignition zone, MBI was calculated as the area fraction of fuel burned in the fuel bed after initial ignition. A successful fire spread had MBI = 1.0, and fires that went out had MBI value in a range of $0 < \text{MBI} < 1$. Near the marginal slope percent, the MBI value was observed to be close to 1.0.

Figure 3 illustrates the MBI values obtained from a group of marginal burning experiments for a range of slopes and various burning conditions. For chamise with $\delta = 0.2$ m, it is found that all MBI values increased with upslope percent. Over a narrow range between 30% and 40%, there was a sharp increase in MBI values from 0.25 to 1. The data suggests that there exists a critical slope (40% for chamise for the conditions in Fig. 3) above which fire spread in these live fuels was successful, and below which fire spread was unsuccessful. This result is consistent with other researchers' observation [4,28] that there is a critical inclination angle for the change of fire behavior and fire spread rate. The convective heat transfer rate would be greatly enhanced around the critical slope leading to a successful fire spread. It is well known that high moisture content can hinder the burning of cellulosic fuels. For manzanita with $M = 82\%$, Fig. 3 shows that the critical slope increases to 50%. This indicates that the marginal slope percent varies with fuel moisture content. Fuel bed depth (or fuel loading) also increases the probability of fire spread success. For chamise with doubling of δ to 0.4 m, Fig. 3 shows that all fire spread cases were successful even in downslope condition. Another important factor that affects marginal burning is the ambient wind [10,11]; however, this is not considered in this paper.

Figure 4 illustrates the MBI obtained from marginal burning experiments with ceanothus and scrub oak. For upslope fire spread, there is a critical slope of 40% for ceanothus and 50% for scrub oak. For downslope fire spread, as expected, the effect of slope on marginal burning was not as sensitive as in the case of upslope fire because of decreased heat transfer rate from convection and radiation. Figure 4 illustrates that all fires went out. For ceanothus the MBI decreased with slope from 0 to −70%. However, for scrub oak, the MBI increased to a maximum value of

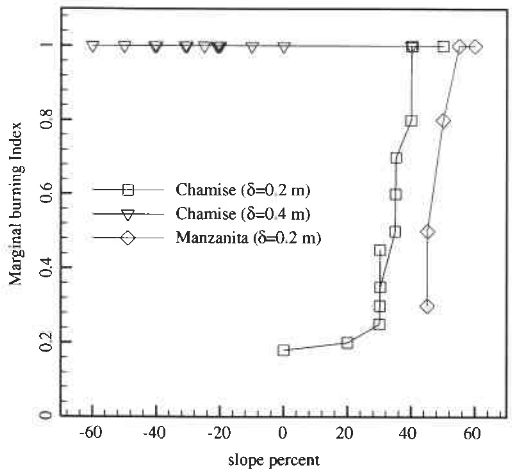

Fig. 3. Marginal burning index obtained from experiments for various burning conditions: chamise ($\delta = 0.2$ m, $M = 58\%$, $L = 1.7$ kg/m^2, $T_a = 23$ °C, RH = 49%); chamise ($\delta = 0.4$ m, $M = 59\%$, $L = 3.4$ kg/m^2, $T_a = 29$ °C, RH = 42%); and manzanita ($\delta = 0.2$ m, $M = 82\%$, $L = 2.7$ kg/m^2, $T_a = 25$ °C, RH = 43%).

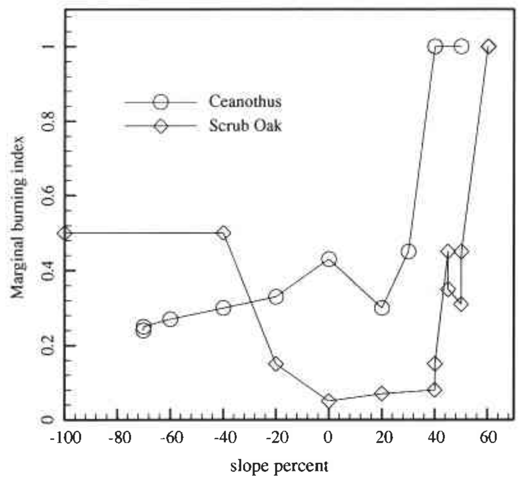

Fig. 4. Marginal burning index obtained from experiments for various burning conditions: ceanothus ($\delta = 0.2$ m, $M = 57\%$, $L = 2.1$ kg/m^2, $T_a = 34$ °C, RH = 32%), and scrub oak ($\delta = 0.2$ m, $M = 65\%$, $L = 1.8$ kg/m^2, $T_a = 34$ °C, RH = 33%).

0.5 with slope from 0 to −100%. It was observed from downslope experiments that some tiny fire brands fell to the unburnt fuels due to gravity. These fire brands might act as igniters to aid burning, but this contribution was hard to judge.

Based on 173 marginal burning tests for no wind and different slopes, fuel moisture content, fuel loading, and ambient conditions, a statistical model was developed to estimate the probability of fire spread success. It is expected to provide guidelines for prescribed burning success. Because the response variable (spread success) was binary, a stepwise logistic regression method was used. The result of this model is

$$X = -0.34 + 0.05Sl + 1.89L + 0.12T_a - 0.11M$$
$$Pr(\text{success} = Y) = e^X/(1 + e^X) \quad (2)$$

The probability Pr of fire spread success was set equal to the function of parameters Sl (slope percent, %), L (kg/m^2), T_a (°C), and M (%). The fitted model correctly classified nearly 86% of the 173 fires in the data. This equation is different from our earlier equations [10,11] because a different subset of the entire data set was used for estimation. When the data set is better balanced, a logistic model will be developed from the entire data set.

The slope of the fuel bed influenced not only the marginal burning characteristic, but also the fire spread rate. Fire spread rate is an important variable in wildfires since it is indicative of the potential fire intensity and fire danger. For successful fire spread tests, Fig. 5 illustrates fire spread rate in chaparral fuel beds as a function of slope percent from −70% to 70%. Fuel moisture content, fuel loading, and ambient conditions vary between data points. Figure 5 shows that the effect of slope over the range −70% to 30% on fire spread rate is relatively minor. For slopes above 40%, the fire spread rate increases greatly because convective heat transfer rate increases greatly around the critical slope. This result is consistent with our analysis in Figs. 3 and 4 on the effect of slope on MBI, and agrees with the results obtained by other researchers [4,8,28].

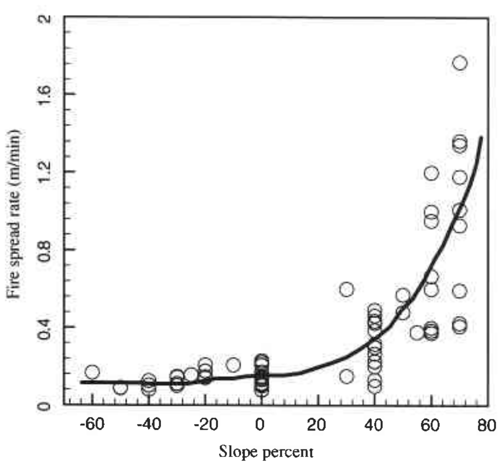

Fig. 5. Fire spread rate plotted as function of the slope percent.

5. Conclusions

In examining two fuel bed slope setups, the large eddy simulation approach is useful in analyzing the detailed fire structure and the coupled physical processes. Upslope fire spread depends not only on the increased radiant heat transfer rate but also on the aerodynamic effect created by the interaction of the flame with the inclined platform. Under our experimental conditions, the convective heat transfer induced by this interaction becomes the dominant mechanism in determining fire spread success. Experimental results demonstrate that there exists a critical marginal slope below which fire spread is unsuccessful, and above which it is successful. This varies with fuel moisture content and fuel loading. Using a stepwise logistic regression method to analyze these 173 fires, a logistic model was developed to predict the probability of fire spread success. It is clear that the combined effects of wind and slope are not adequately modeled. Further work is still needed to improve the current LES approach, and to obtain more detailed experimental data to validate the numerical model.

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Comments

Juan de Dios Rivera, Universidad Catolica de Chile, Chile.

1. How did you ignite the fuel bed?
2. Did you notice any effect at the side walls on quenching or reducing the flame propagation rate in its vicinity?
3. Did you weigh the remaining char, in order to determine the percent of the fuel that actually burned?
4. Have you considered any re-radiation of the ground into the fuel bed?

Reply. The ignition of the fuel bed was described in detail in the experimental setup, section 2. For numerical modeling, the ignition of the fuel bed was simulated by introducing a volumetric heat source over the entire fuel bed depth and along a length of 20 cm. This heat supply is maintained until 70% of fuel in the ignition zone is burned out.

Because air entrainment from the lateral sides of the fuel bed was prevented by metal sheeting, it was found that most of the experimental fires maintain a rectilinear shape. The effect of the side walls on quenching or reducing the flame propagation rate is minor.

We did not measure the unburned residue after each experimental fire. When the fire spread successfully, virtually all of the fuel was consumed. The marginal burning index describes the percent of the total fuel bed that was unburned.

Because the fuel was elevated 40 cm above the ground, the re-radiation of the ground into the fuel bed was not considered. The ground surface under the fuel bed in the experiments was composed of white, insulating fire brick. While the brick did heat up somewhat due to radiant heat transfer, the amount of energy re-radiated was minimal given that the brick did not reach 100 °C for the duration of the experiment.

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Carlos Fernandez-Pello, University of California Berkely, USA. Heat transfer by conduction and radiation in the porous fuel bed can be an important mechanism of fire spread. Have you considered these effects in your analysis?

Reply. Heat transfer by conduction might be minor but radiation is important. The term $QA_{\mathrm{rad,s}}$ represents the radiative heat transfer received by a particle in the fuel bed. By virtue of the particle's location, all radiative heat transfer is through the porous fuel bed—

either from the flame above the fuel bed or from the flame zone within the fuel bed. At this point in time, the model does not distinguish between these two sources. Due to the fuel bed porosity in this experiment, the mean free path for radiant heat transfer is about 16 cm.