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Analysis of ladder fuel ignition through experiments and fire dynamics simulator simulation

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Abstract

Background Prescribed burning is an important silvicultural tool used to reduce wildfire hazard by removing accumulated forest floor debris to improve wildlife habitat and to mimic the natural role of fire in the environment. Ladder fuels, which provide vertical fuel continuity between ground and crown fuels, pose a risk to the use of prescribed burning by increasing the likelihood that a surface fire may spread vertically resulting in undesirable fire behavior and unplanned fire effects. To minimize this risk, an improved understanding of the ignition criteria of ladder fuels is essential. We investigated the effect of ambient temperature, relative humidity, plant species, live fuel moisture content, live fuel bulk density, season of year, and fuel base height on ladder fuel ignition success via 92 controlled experiments. Ladder fuels were live manzanita and incense cedar foliage and branches placed above a surface fire burning in a pine needle fuel bed. In addition, we applied the Fire Dynamic Simulator (FDS), a Computational Fluid Dynamics (CFD) based model specifically designed to simulate fire scenarios, to replicate the experiment and compare the results with the experimental data.

Results Using experimental data, we developed a logistic-regression model that characterizes empirical relationships and allows rapid estimation of ignition probability. The results show that ladder fuel burning behavior is highly sensitive to ambient temperature, fuel species, and fuel base height: ignition probability increases with temperature and varies systematically across species, while increasing fuel base height substantially reduces the likelihood of ignition. Moreover, FDS predictions are in good agreement with our experimental outcomes, reinforcing the robustness and potential applicability of FDS for operational prescribed-fire planning and risk assessment.

Conclusion The experimental results provide a more comprehensive understanding of the ladder fuel ignition. The empirical logistic model offers an operationally useful basis for anticipating ladder-fuel ignition. The experimental data also supplies novel and realistic validation cases for FDS. The empirical ignition-prediction model as well as FDS can be incorporated to inform burn prescriptions, refine go/no-go decisions, and ultimately support safer, more effective use of prescribed fire.

Keywords Prescribed burning, Wildland fire, Fire spread experiment, CFD, Numerical simulation

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Resumen

Antecedentes Las quemas prescriptas representan una herramienta silvicultural importante para reducir el riesgo de fuegos de vegetación, mediante la remoción del material leñoso superficial y otros residuos vegetales, y mejorar así el hábitat para la fauna y para reproducir artificialmente el rol natural del fuego en el ambiente. Las escaleras de combustible, que proveen de continuidad vertical a los combustibles vegetales entre el suelo y las coronas de los árboles, ponen en riesgo el uso de las quemas prescriptas al incrementar la probabilidad de que un fuego superficial pueda propagarse verticalmente y se transforme en un incendio de comportamiento indeseable y con efectos adversos. Para minimizar este riesgo, es esencial un mejoramiento en el entendimiento de los principios de la ignición en las escaleras de combustible. Investigamos el efecto de la temperatura ambiente, la humedad relativa, las especies vegetales, el contenido de humedad del combustible vivo, la densidad aparente de los combustibles, la estación del año, y la altura de la base del combustible vegetal, sobre el éxito de la ignición a través de 92 experimentos controlados. Las escaleras de combustible fueron hojas verdes y ramitas del árbol conocido en California como "manzanita" y también de cedro incienso (*Calocedrus decurrens* (Torr.) Florin (1956)), colocadas por encima de un fuego superficial cuya cama de combustible eran acículas de pino. Adicionalmente, aplicamos el Simulador de la Dinámica de Fuegos (FDS), un modelo computacional basado en la dinámica de fluidos (CFD) específicamente diseñado para simular escenarios de fuegos, de manera de replicar el experimento y comparar los resultados con los datos experimentales.

Resultados Usando datos experimentales, desarrollamos un modelo de regresión logística que caracteriza relaciones empíricas y permite una rápida estimación de la probabilidad de ignición. Los resultados muestran que el comportamiento del fuego en las escaleras de combustible es altamente sensible a la temperatura ambiente, al combustible vegetal de cada especie, y a la altura de la base del combustible; la probabilidad de ignición se incrementa con la temperatura y varía sistemáticamente entre especies, mientras que el incremento de altura de la base del combustible reduce sustancialmente la probabilidad de ignición. Además, las predicciones con el FDS concuerdan con nuestros resultados experimentales, lo que refuerza la robustez y potencial aplicación del FDS para el planeamiento de operaciones de quemas prescriptas y la determinación del riesgo.

Conclusiones Los resultados experimentales proveen de un entendimiento comprensivo de la ignición de escaleras de combustible. El modelo empírico logístico ofrece una base operacional útil para poder anticipar la ignición en escaleras de combustible. Los datos experimentales proveen también de validación realística para casos de FDS. El modelo empírico de predicción de la ignición junto con el FDS pueden ser incorporados para informar sobre prescripciones de quemas, refinar las decisiones de "hacer o no hacer", y por último, para apoyar decisiones seguras y más efectivas en el uso de las quemas prescriptas.

Background

Prescribed burning is the use of "intentional ignitions designed for specific resource management objectives" (Hiers et al. 2020). These fires are typically the planned application of fire under predefined fuel and meteorological conditions using various ignition patterns to produce desired fire behavior and effects (Biswell 1989). The transition of fire from surface to elevated fuels is a significant factor in the energy release and fire behavior in a wildland fire. This transition is defined as the process where a spreading surface fire moves vertically to ignite elevated fuels (Cobian-Iñiguez et al. 2022; Weise et al. 2018). Expanding our knowledge on predicting this vertical transition is important for evaluating treatment effectiveness and for informing prescribed-burn planning.

Previous studies have explored factors influencing this vertical transition among a range of fuel types. In shrub fuels, researchers have explored how fuel properties and environment affect ignition and upward spread (Tachajapong et al. 2008; 2009; 2014; Lozano et al. 2010; Lozano 2011; Cobian-Iñiguez et al. 2017; 2022; Weise et al. 2018). Additional work has focused on coniferous forests (e.g., Van Wagner 1977; 1993; Albini and Stocks 1986; Albini 1986; 1996; Butler et al. 2004; Cruz et al. 2006a, b). Dual layer systems have been used to study vertical fuel ignition criteria and fire transitions. Tachajapong et al. (2008) conducted studies on dual layers to investigate the impact of elevated fuel bulk density on the dynamics of fire initiation in shrublands. Observations indicated that ignition occurred when the elevated fuel was within the continuous flame region (McCaffrey 1979). Additionally, higher fuel bulk density led to quicker fire ignition. In another dual layer study, Tachajapong et al. (2009) studied the transition of surface fire to wet shrub fuels and observed that an increase in base height led to a decrease in the likelihood of fire initiation. Cobian-Iñiguez et al. (2022) found that the presence of wind enhanced vertical fire spread behavior greatly. Both the surface and elevated fuels exhibited substantially higher heat release rates in the presence of wind compared to no-wind conditions, indicating increased flame intensity with wind.

The current study explores the ignition criteria of two ladder fuels, manzanita and incense cedar. Ladder fuels are combustible materials that can act as a "ladder" for a surface fire to move vertically from the ground into a forest's canopy. Ladder fuels typically consist of smaller trees, shrubs, and the lower branches of larger trees. Ladder fuels carry fire from the forest floor to the canopy and thereby may turn low-intensity fires into severe canopy fires. To reduce the risk of such fire, the height between the floor to the tree crowns is increased by mechanically removing the ladder fuels up to a certain height deemed to be sufficient and feasible operationally (e.g., Agee 1996; Mruzik 2001; Menning and Stephens 2007). However, ignition of elevated ladder fuels depends not only on geometric separation but also on the characteristics of the surface flame and the duration of heating. To examine these processes under controlled conditions, we adopted a dual-layer system consisting of a surface fuel bed and an elevated fuel bed. We recorded time to ignition for elevated ladder fuels across species, seasons, ambient temperatures, and fuel-base heights (the distance between elevated and surface fuels).

In addition to experimental work, empirical and numerical models have been widely used to study wildfire ignition criteria. Agee (1996) estimated minimum flame lengths necessary to initiate crown fire spread for ranges of foliar moisture content and crown base height using the empirical model developed by Van Wagner (1977) and the flame length-fireline intensity model developed by Byram (1959). Agee's work may be one of the first instances where models were coupled to estimate wildfire ignition risk. In recent years, comprehensive numerical models have been developed to predict the fire ignition and transition. For example, Cruz et al. have developed a crown fire initiation model (CFIM) to predict the transition of a surface fire to a crown fire (Cruz 2004; Cruz et al. 2006a, b). CFIM was validated through sensitivity analysis and comparison with fire behavior data from high intensity prescribed fires (Cruz et al. 2006a, b). Other work used Monte Carlo simulation to produce more robust results compared to a deterministic model of crown fire transition (Cruz and Alexander 2017). This modeling approach was applied to fuel treatments in Monterey pine (*Pinus radiata* D.Don) plantations in South Australia. The modeling results suggested that the fuel treatments greatly reduced crown fire potential. Tachajapong et al. (Tachajapong et al. 2008; 2009; 2014; Lozano 2011) and Albini et al. (Albini 1985; 1986; 1996; Albini and Stocks 1986; Butler et al. 2004) used physics-based modeling to investigate crown fire initiation (Morvan 2011). Another physics-based CFD model, the Fire Dynamics Simulator (FDS) (McGrattan et al. 2024b), has been used to model fire spread horizontally through vegetative fuel beds and vertically through single trees (Mell et al. 2007; 2009). FDS is a CFD code developed by NIST to model fire-driven flows. It solves the Navier–Stokes equations with large-eddy simulation (LES) turbulence, emphasizing smoke and heat transport. FDS has also been compared with various experimental data, demonstrating its capability to reproduce key fire dynamics under various conditions (Hoffman et al. 2016).

In addition to expanding knowledge of ladder fuel ignition through experiments, the current experiment dataset enables development of an empirical logistic model that predicts elevated fuel ignition. Moreover, the well-characterized dataset serves as a novel validation case for FDS. The FDS modeling results complement the measurements by enabling direct model-experiment comparison of ignition behavior and associated quantities and allowing the findings to be applied across a broader range of conditions than could be tested experimentally.

In this study, we combined controlled experiments and modeling approach to evaluate ignition of elevated ladder fuels. To isolate the effect of the moving surface fire and its rate of spread, the current study implemented a conveyor belt system similar to that used by Fons et al. to generate a stationary surface source fire and report the exposure duration (Fons et al. 1961; Jenkins et al. 1996). This paper presents: (1) experimental measurements of ambient conditions, flame temperature, and fuel mass loss rate under 92 controlled experiments (2) a logistics regression model based on the experimental data that can predict fire ignition to inform prescribe burns planning based on simple inputs and (3) a comparison between experimental results with FDS simulations conducted under identical conditions, serving as a novel validation case for FDS. Detailed descriptions of the experimental setup and methodology are provided in the following sections.

Methods

Experimental setup

Ladder fuels in forests are often shrubs and small trees. In California, there are numerous shrub and tree species in the mixed evergreen and midmontane forests (Barbour and Minnich 2000) that can be ladder fuels. Two local species, Eastwood's manzanita (*Arctostaphylos glandulosa* Eastw.) and incense cedar (*Calocedrus decurrens* (Torr.) Florin), were selected to represent shrub and tree ladder fuels, respectively (Fig. 1). The manzanita was collected from the North Mountain Experimental Area (33.85205 N, −116.87613 W) and incense cedar was collected near Jenk's Lake on the San Bernardino National Forest (34.16261 N, −116.89922 W). Both collection sites

Fig. 1 (**a**. top) Incense cedar trees; (**a**. bottom) Foliage and branches of incense cedar; (**b**. top) Manzanita shrubs; (**b**. bottom) Foliage and branches of manzanita. Incense cedar and manzanita represent tree and shrub ladder fuels respectively. Samples did not include flowers or fruit

were within 80 km of the burn facility at the USDA Forest Service PSW Research Station in Riverside, CA, USA, enabling the daily collection of the live foliage attached to branches to minimize moisture loss. The experiments were conducted during summer and winter from July 2022 to April 2023, since live fuel moisture content varies over the year and these seasons represent the low and high values of live fuel moisture in southern California (Countryman and Dean 1979; Weise et al. 2005).

The experimental setup consisted of a surface fuel bed composed of longleaf pine needles (*Pinus palustris* Mill.) and an elevated fuel bed (Fig. 2) of either incense cedar or manzanita. The effects of fuel moisture, plant species, and vertical distance from the surface fire source were investigated in a series of 92 experimental fires. Surface fuel bed dimensions were 170 x 70 x 5 cm (length x width x depth) and 1.2 kg of pine needles (fuel load of 1 km/m^2) were distributed uniformly (Schuette 1965). The use of dead pine needles in the surface fuel bed was consistent with earlier work that used excelsior (shredded *Populus tremuloides* Michx. wood) as the dead fuel instead of gas burners or liquid pool fires (Tachajapong et al. 2009; Lozano 2011; Cobian-Iñiguez et al. 2022).

The experiment setups and procedures are as follows:

1. For each experiment, 1.2 kg of pine needles were distributed uniformly as the surface fuel bed. 0.6 kg of the ladder fuel (either incense cedar or manzanita) was suspended in a 1 m x 1 m basket hooked above the surface fuel bed. After the two fuel beds were prepared and leveled to a uniform thickness, the dimensions (length, width, and height) were

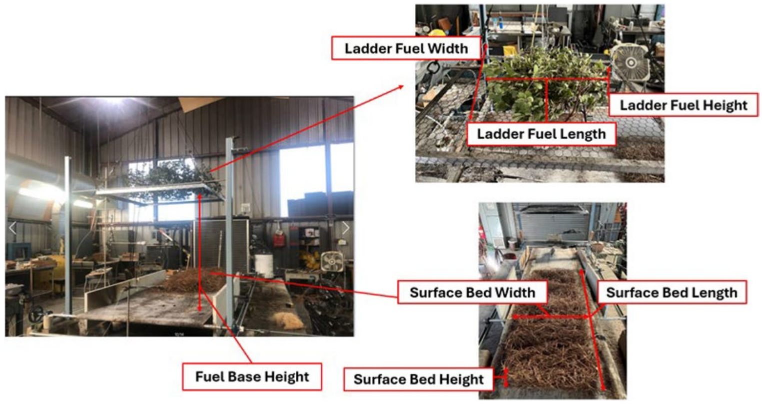

Fig. 2 The dual-layer experiment setup used to simulate ignition of ladder fuels by a surface fire. The surface fuel bed is made of pine needles and the elevated fuel bed shown in the example is composed of manzanita

then measured relative to a consistent reference plane using a rigid ruler at a fixed, pre-defined location to ensure repeatability across experiments. These dimensions were then used to calculate fuel volume and bulk density.

2. An Omega S Beam[1] load cell with a precision of 0.001 g is mounted on a cord which is looped around the lower hook of the chain hoist, the load cell is wrapped in an insulating sheet to protect the load cell from the flames of the ladder fire. The load cell measured the instantaneous mass of the ladder fuel bed during the experiment, which was used to calculate the ladder fuel mass loss rate.
3. Fuel base height (FBH), the vertical distance between the top of the surface fuel bed and the bottom of the ladder fuel bed, was set to different heights to vary the flame exposure of the ladder fuel bed (75 cm, 85 cm and 95 cm).
4. Type K unsheathed fine gage thermocouples which have a wire diameter of 0.075 mm, and a response time of 0.2 s were mounted at different heights along the centerline of the flame to measure the temperature at various heights. The measurements were adjusted for radiant heat loss based on energy balance; details can be found in (Nishandar 2023). The thermocouples were positioned at the height of 15 cm, 55 cm, FBH + 10 cm and 105 cm. The third thermocouple was inserted into the bulk of ladder fuel and adjusted to change height in accordance with the FBH for different experiments.
5. Prior to ignition, approximately 100 g of the ladder fuel was set aside in a sealed container to determine fuel moisture content following standard test methods (ASTM 2020). The sealed sample containers were transferred to a drying oven to remove moisture, after which the Fuel Moisture Content (FMC) of each sample was calculated. The same procedure was applied to measure the FMC of the surface fuel pine needles on each experimental day.
6. Prior to ignition, the ambient temperature and relative humidity were measured using a thermos hygrometer.
7. Ignite the pine needle surface fuel bed using a propane torch along the 0.7 m edge to produce a line fire.
8. A designated conveyor-belt operator controlled the belt via a pulley system and rapidly positioned the surface flame beneath the center of the ladder fuel bed, where the surface flame was maintained for the duration of the experiment.
9. Visible and thermal infrared cameras (FLIR 640) recorded each experiment. Each experiment ended when either the ladder fuel bed ignited, or the surface fuel bed burned out.
10. Tests were categorized as ’ignited’ if the elevated fuel was ignited and sustained a flame for at least 10 s; otherwise, they were classified as ’non-ignited’.

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Logistic regression model

Since the response variable was binary (ignited or non-ignited), a logistic regression model was used to determine which of the experimental factors (moisture content, plant species, fuel base height, season, bulk density, and air temperature) significantly affected the probability of ignition. Stepwise forward selection was implemented and the reduction in the Akaike Information Criterion (AIC) was used to select variables. The selection process began with a model containing only the intercept, variables were added sequentially and tested based on their contribution to the decrease in AIC.

FDS model setup

The current version of FDS (6.9.1) was used in the present study. While the use of FDS to model burning vegetation has been increasing over the past 2 decades, the number of large-scale experimental datasets is limited due to the logistical and resource-intensive requirements of conducting such experiments. FDS simulations were conducted under the same configurations to (I) provide an independent, physics-based reproduction of the tested cases for direct comparison of ignition behavior and associated quantities, and (II) support application of the experimental findings to conditions beyond the specific test matrix.

Grid cell resolution in the simulations was 10 cm (grid size is selected referring to study from (Mell et al. 2009) due to the similar scale) with a computational domain of 2.4 m × 2.4 m × 7.2 m (Fig. 3). The ladder fuel was represented by a 0.6 kg mass of uniformly distributed cylinders above the surface fuel. Since foliage and branches had different physical characteristics (e.g., Countryman and Philpot 1970; Countryman 1982; Gallacher et al. 2017), the fractional mass of the ladder fuel bed was measured to be 0.4 foliage and 0.6 branches. Average fuel moisture content for incense cedar (107%) during the summer was adopted as model input. Ash content of the fuel was assumed to be 4%. Physical characteristics of these fuel particles are listed in Table S1. The surface fuel bed (ignition source) was modelled as a constant heat source 0.7 m × 0.2 m × 0.05 m with heat release rate per unit area of 400 kW m^{-2}.

The FDS model numerically solves the governing equations for fluid flow, combustion, heat transfer, and thermal degradation of the vegetative fuel (Mell et al. 2009) which was modelled using the Lagrangian particle method. Further details of the modeling of the evaporation, pyrolysis and combustion of vegetation can be found elsewhere (McGrattan et al. 2024b; 2024a). The thermal degradation of the fuels was assumed to be default in the model. The time series of the mass of the elevated ladder fuel were recorded. Given that the temporal resolution of the dataset was 0.2 s per data point, mass values were averaged over every five time steps to produce data representative of each second. The simulated values were compared with the observed experimental results.

Results

Experimental results

Tests that occurred between July and October were classified as summer burns and between November and April as winter burns. The range in air temperature and in relative humidity in the unconditioned burn laboratory were similar for the two ladder fuel species (Table 1).

The bulk densities of the incense cedar fuel beds (15.5 ± 5.1 kg/m^3) tended to be higher than the manzanita fuel beds (9.95 ± 2.65 kg/m^3). This is due in part to the physical structure of foliage; incense cedar foliage tends to be more two dimensional than manzanita foliage due to their growth form and environment.

Figure 4 presents the fuel moisture content for ladder fuels and surface fuel. Incense cedar tended to have 38.8% and 32% higher FMC than manzanita in summer and winter respectively. Mean FMC of manzanita was 65.8 and 74.9 percent, while for incense cedar mean FMC was 107.6 and 111.4 percent for summer and winter, respectively. This was also indicative of the site conditions for these two species. Manzanita samples were collected from chaparrals, which were at lower elevation on a drier

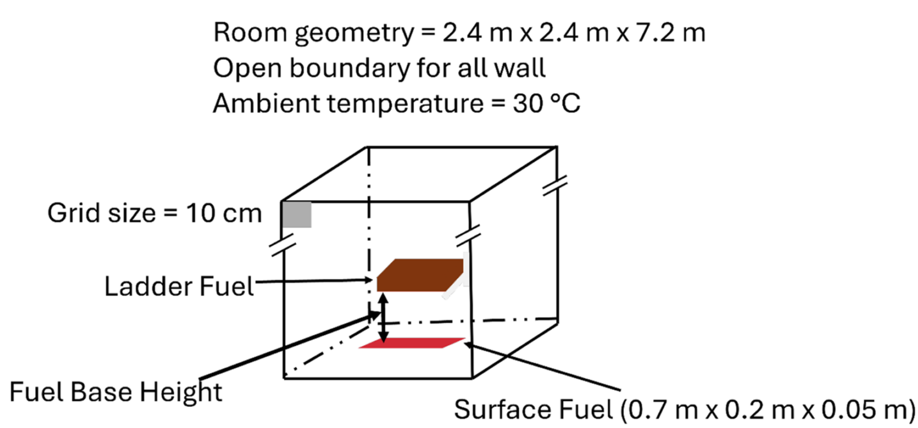

Fig. 3 Schematic of computational domain for the Fire Dynamics Simulator used to model the heating and potential ignition of an elevated ladder fuel by a stationary surface fire

Table 1 Summary of conditions for summer and winter experimental burns to test ignition of two types of ladder fuels. Values are mean, minimum and maximum observed values

Season	Species	Air Temperature (ºC)	Relative Humidity (%)	Fuel Bulk Density (kg/m^3)	Fuel Moisture Content (%)
Summer	Manzanita	32.7 (26.5–39.5)	41.3 (29–63)	10.5 (6.2–16.5)	65.8 (48.3–78.5)
	Incense cedar	28.9 (24.0–33.3)	43.2 (28–65)	18 (11.5–30.6)	107.6 (88.2–138.3)
Winter	Manzanita	16.2 (10.2–22.5)	41 (14–78)	9.3 (4.5–15.1)	75.2 (57.6–91.6)
	Incense cedar	20.01 (11.5–24.2)	17.6 (12–24)	13.6 (6.7–22.4)	111.4 (52.5–123.5)

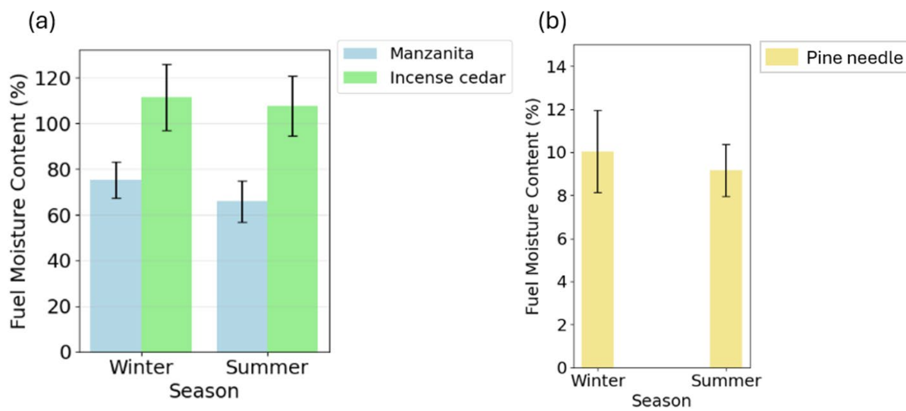

Fig. 4 Fuel moisture content for (**a**) ladder fuels and (**b**) Pine needle

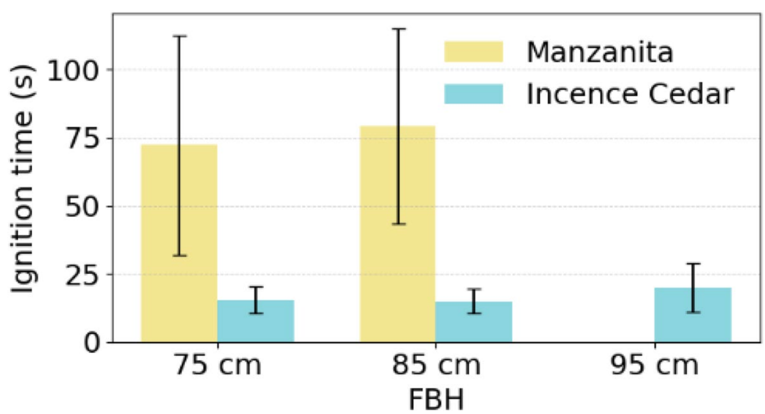

Fig. 5 Ignition time for ladder fuels at different FBH

southerly aspect while the incense cedar montane forest site was higher elevation with a northerly aspect (Fig. 5).

For incense cedar, the mean ignition time was 15.38 ± 5.02 s when FBH = 75 cm, 15 ± 4.55 s when FBH = 85 cm, and 20 ± 8.83 s when FBH = 95 cm for ignited cases. For manzanita, the mean ignition time was substantially longer than incense cedar, when FBH = 75 cm, it was 72.2 ± 40.42 s, when FBH = 85 cm, it was 79.2 ± 35.65 s, when FBH = 95 cm, there wasn't ignited case.

The large standard deviations reflect substantial variability in ignition times across individual burns. These variations are likely due to uncontrollable factors inherent in large-scale experiments, such as branch placement, moisture content, bulk density, and the specific composition of leaves and wood within the ladder fuel structure.

Logistic regression

A total of 92 ladder fuel ignition tests were conducted between April 2022 and Jun 2023. Of these, 45 fuel beds

Table 2 Summary of ignition success for ladder fuels by species, season and vertical distance in cm between surface fuel bed and ladder fuel bed (FBH)

Season	FBH	Species			
		Manzanita		Incense cedar	
		Y	N	Y	N
	75	6	2	6	0
Summer	85	4	5	6	0
	95	0	9	2	4
	75	4	4	8	0
Winter	85	0	8	7	1
	95	0	8	2	6

ignited successfully and 47 did not (Table 2). The stepwise fitting process chose three independent variables (Table 3, (Eq. 1)): ambient temperature, fuel base height and ladder fuel species.

$$\pi(\boldsymbol{x}) = \frac{exp(13.52 + 0.12T - 0.21FBH + 3.52Sp)}{1 + exp(13.52 + 0.12T - 0.21FBH + 3.52Sp)} \quad (1)$$

The probability of ladder fuel ignition is between 0 and 1, T is ambient air temperature, FBH is the height of the ladder fuel above the surface fuel bed and Sp is ladder fuel species. The model correctly classified 76 of the 92 fires. Based on the coefficient estimates, the likelihood of ignition increased as air temperature increased and decreased as the distance between the surface fuel bed and the ladder fuel bed increased. Manzanita was coded as 0 and incense cedar as 1 which meant that incense cedar was more likely to ignite relative to manzanita under similar conditions.

To expand the empirical model, we additionally evaluated a composite factor (Carlos G. Rossa and Fernandes 2018a):

$$F = \frac{Qi}{\beta} \quad (2)$$

where Qi is the heat required per unit mass to bring moist fuel to ignition conditions, and β is the packing ratio.

$$Qi = c_f\left(T_i - T_f\right) + \frac{M}{100}\left[c_w\left(T_v - T_f\right) + Q_w\right] \quad (3)$$

where c_f, c_w, T_i, T_f, T_v, Q_w and M are fuel specific heat, water specific heat, fuel igniting temperature, fuel initial temperature, water boiling temperature, water latent heat of evaporation, and fuel moisture content respectively. We consider the physical constants in Eq. 3 to be c_f = 1.72 kJ/kg· °C, c_w = 4.19 kJ/kg· °C, T_i = 320 °C, T_v = 100 °C, and Q_w = 2260 kJ/kg (Rossa 2018). T_f is assumed to be equivalent to ambient temperature.

$$\beta = \frac{bulk\ density}{particle\ density} \quad (4)$$

We consider the particle density = 630 kg/m^3 (Carlos G Rossa and Fernandes 2018b). Smaller β indicates looser fuel bed, and more flame energy passes through gaps instead of heating particles (Rossa et al. 2015).

We then treat F and FBH as dependent variables in the fitting process:

$$\pi(\boldsymbol{x}) = \frac{exp\left(28.18 - lg(F) - 0.13FBH\right)}{1 + exp\left(28.18 - lg(F) - 0.13FBH\right)} \quad (5)$$

The regression results are presented in table S2. This expanded model correctly classified 66 of the 92 fires. We applied this factor because species coefficient is inherently not extrapolatable in the previous empirical model, which only encodes incense cedar and manzanita. While this formulation (Eq. 2) provides a generalizable pathway to extend to additional fuel types, as F is defined from measurable physical properties applicable to any fuel bed.

Temperature and mass loss sequences

Temperature and mass loss sequences for incense cedar ladder fuel beds at 75 cm, 85 cm and 95 cm above the surface fuel bed are presented in Fig. 6. The temperature is measured inside the ladder fuel bulk. The rapid rise in the temperature is associated with successful ignition. When FBH = 75 cm, the selected burn shows a rapid ignition, when FBH = 85 cm, the time to ignition is longer, when FBH = 95 cm, no ignition is observed in the selected burn.

Table 3 Logistic regression results for predicting successful ignition of elevated layer fuel

Variable	Coefficient	Standard Error	P-value	97.5% CI	Akaike Information Criterion
Intercept	13.517	3.8	0.000	(6.053, 20.981)	
FBH (cm)	−0.215	0.05	0.000	(−0.314, −0.116)	110.15
Fuel Type	3.52	0.816	0.000	(1.919, 5.117)	85.59
Temperature (°c)	0.124	0.045	0.006	(0.035,0.212)	78.52

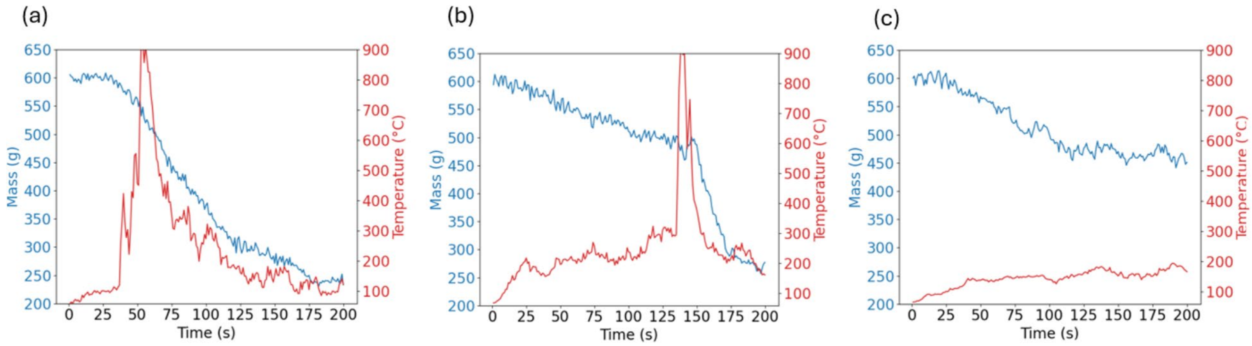

Fig. 6 Temperature profiles and ladder fuel mass loss when FBH = 75, 85 and 95 cm respectively during summer season (burn number 67, 74 and 70 refer to table S3 experimental results for the burning characteristics) measured by Type K thermocouples and Omega S Beam load cell. The temperature is measured within the ladder fuel bed. (**a**) and (**b**) ignited while (**c**) is not ignited

The mass of the ladder fuel bed decreased gradually or rapidly depending on the height of the ladder fuel above the surface fuel bed. The gradual mass loss at an FBH of 95 cm did not result in ignition. The mass loss was likely due to water evaporation and perhaps the volatilization of low vapor pyrolyzates in that case. In all cases, the initial phase exhibited a similar trend, with mass loss primarily due to moisture evaporation and pyrolysis. Upon ignition, the mass loss dropped rapidly for the ignited cases. The sharp drop in mass occurred sooner for FBH = 75 cm compared to FBH = 85 cm.

FDS simulation

Figure 7 presents a visual comparison between a simulation and experiment. The ladder fuel is suspended above the surface, represented by the brown obstacles. The FDS visualization is from Smokeview.

Figure 8 shows the mass loss comparison between FDS and experimental results for incense cedar ignited cases when (a) FBH = 75 cm and (b) FBH = 85cm. As indicated in Fig. 8, the trend exhibited a gradual decrease during pyrolysis and moisture evaporation initially, upon ignition, there was a notable and rapid increase in mass loss during the flaming phase. As the elevated fuel approached near depletion, the combustion transitioned to a smoldering phase, and the mass loss decelerated again. The simulated temporal mass loss aligns reasonably with the experimental results, though some deviations in absolute values occurred due to model simplifications, as also observed in (Linteris et al., 2004). Additionally, moisture

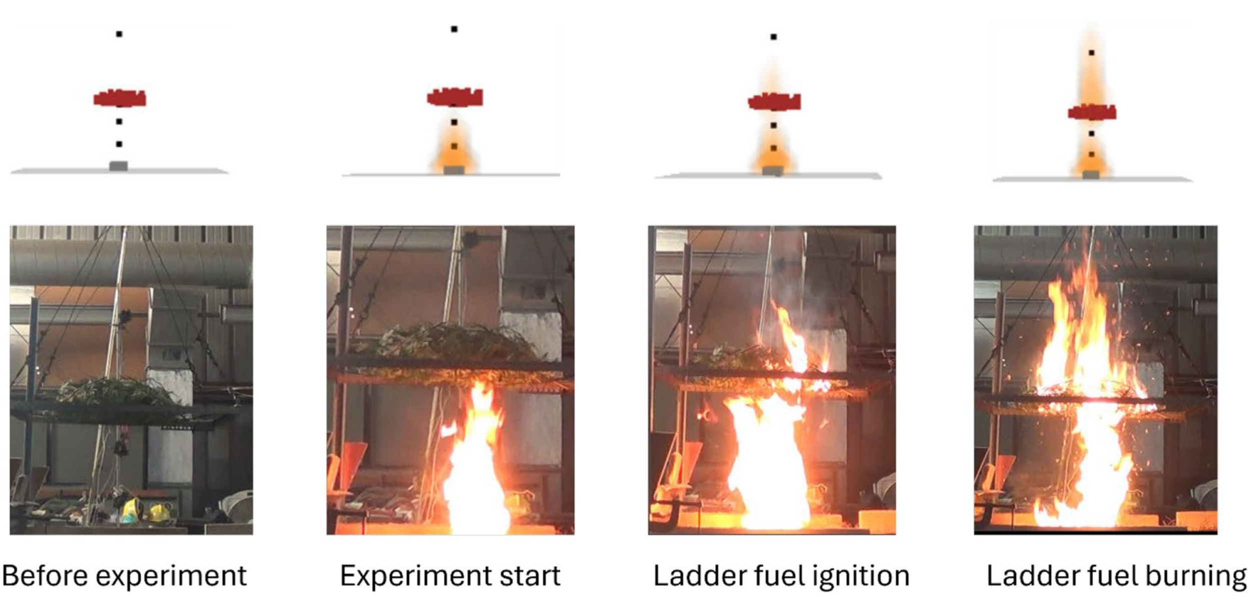

Fig. 7 Visual comparison between simulation and experiment for the four stages of one burn

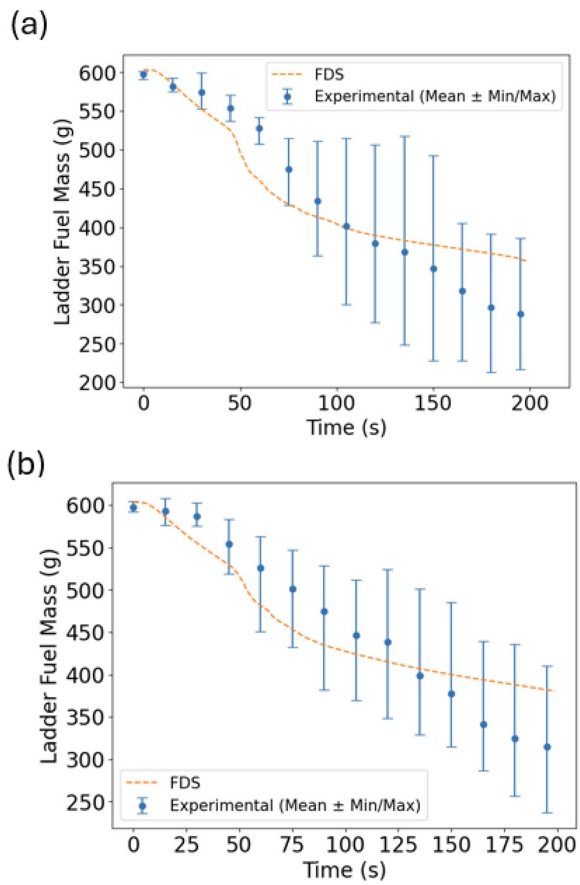

Fig. 8 Mass loss comparison between FDS and experimental results for incense cedar for fuel base height (FBH) of (**a**) 75 cm (burn 67, 72, 73, 81) and (**b**) 85 cm (burn 66, 71, 74, 80, 83). Error bars are the standard deviation based on different burns. (burn numbers are characteristics refer to Table S3)

loss occurs more rapidly in FDS because the imposed heat flux is spatially and temporally uniform, whereas in the experiments the heat flux from the ignition source is inherently variable due to flame flicker.

Discussion

Some other studies have also applied logistic regression on experimental data to identify the significant variables leading to fuel ignition. Zhou et al. assessed impact of species, slope, fuel bed depth, and wind velocity, etc. on marginal burning in live chaparral fuel beds (Zhou et al. 2005). Among the 10 predictor variables tested, wind speed, slope, dry fuel loading, relative humidity and fuel moisture content were found to be significant in successful marginal fire spread. Dimitrakopoulos et al. conducted similar ignition probability assessment for Mediterranean grass fuel in Greece (Dimitrakopoulos et al. 2010). They selected five ignition trials during a single test at the same time during a day. The parameters including ambient air temperature, humidity, wind speed and fuel moisture content are recorded and assessed in their logistic regression. They found that the fuel moisture content was statistically significant in this grass ignition test. It is worth noting that their study is valid for short duration sustained flaming for surface fuel.

We observed a clear species effect: incense cedar demonstrated quicker ignition compared to manzanita under similar ambient conditions. Two reasons may cause this phenomenon. First, incense cedar branches typically have a denser foliage. Branches with more foliage are generally more likely to ignite than branches with fewer leaves or foliage. This is because the foliage increases the surface area of the branch, providing more material for potential ignition. Fuels with a higher SA/V ratio can heat up more rapidly as they are more exposed to heat sources. Research also suggested that broadleaf species may indeed be more fire-resistant than needle-shaped ones (Proença et al. 2010). Second, as Table 1 demonstrates, incense cedar has a higher average fuel bulk density than manzanita, it means incense cedar is more compact, and the velocity of hot gases within the fuel matrix decreases. That means there is less air entrained through the fuel and more energy being accumulated, thereby enhancing ignition probability (Tachajapong et al. 2008).

The laboratory experiments revealed that the ignition of ladder fuels is intricately influenced by ambient temperature, fuel base height and species of ladder fuel. Based on these laboratory results, ambient temperature may be an important variable to consider when defining prescribed fire prescriptions. The heat release rates in the present experiment need to be compared with heat release rates from actual prescribed fires to determine if ladder fuel removal is necessary prior to using prescribed burning. The heat release rate of a prescribed burn can be modified through a variety of prescription variables and firing patterns. Similarly, comparison with heat release rates from low intensity wildfires is necessary to determine if the results can be applied in situations where ladder fuels are being treated to prevent the development of a crown fire in the event a wildfire occurs.

Moreover, the promising alignment between the FDS outcomes and our experimental data supports the potential of FDS as a robust tool in fire management. In practical terms, FDS can help managers simulate different combinations of flame geometry, fuel moisture, and ignition conditions to predict when ladder fuels are likely to ignite. This allows for more precise decisions about whether ladder fuels need to be mechanically removed before burning, or whether adjusting the burn prescription, such as modifying ignition patterns to limit surface heat flux, could reduce ladder fuel ignition risk. Furthermore, the results suggest that dry fuels, even under low surface heat flux, can still ignite (Table S4), reinforcing the need to monitor fuel moisture closely before implementation. Overall, integrating FDS with field measurements can enhance prescribed burn planning by anticipating ignition likelihood under various configurations and improving the safety and effectiveness of fuel treatments.

Conclusion

The current study improved our understanding of ladder fuel ignition. The logistic ignition model provides a simple way to incorporate ladder fuel ignition probability into burn prescriptions by explicitly accounting for ambient temperature, fuel base height, and fuel type, allowing managers to identify combinations of weather and stand structure where prescribed burns are more likely to transition into the canopy and to adjust burn windows or ignition patterns accordingly. Likewise, the strong sensitivity of ignition to fuel base height supports existing guidelines that emphasize mechanical removal or pruning of shrubs and lower branches to increase crown base height before applying fire and suggests that treatment standards could be refined using quantitative ignition thresholds rather than qualitative descriptions. FDS scenario results further demonstrate that modest changes in surface heat flux, live fuel moisture, or geometry can shift outcomes from no ignition to sustained flaming, emphasizing the need for conservative prescriptions during periods of elevated temperatures or unusually dry fuels. Together, the experimental and modeling results highlight how integrating ladder-fuel ignition criteria into burn planning and fuel-treatment design can help expand the safe use of prescribed fire while reducing the risk of unintended crown fire initiation.

Supplementary Information

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Supplementary Material 1

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Authors' contributions

Y.H. wrote the main manuscript text, prepared Fig. 3–8, conducted experiments, modeling work and data analysis. S.R.N. prepared Fig. 2, conducted the experiments and summarized the experimental data. J.Z. supervised the revision of the manuscript. H.L., J.C. and G.B. conducted the experiments. M.P. initialized the project and supervised the experiments. D.R.W. provided funding, supervised the experiments and revision of the manuscript. All authors reviewed and approved the final version.

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Data availability

The data used to generate the results in this paper are listed in supporting information.

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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