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Research article

Comportamiento del fuego y consumo de la capa de hojarasca en bosques de pino-oyamel y pino-encino

Fire behavior and litter layer consumption in pine-fir and pine-oak forests

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Abstract

Fuel load, topography, and fuel moisture influence fire behavior. Knowing these relationships allows us to identify the fire behavior according to the tree community, and whether or not their heterogeneity corresponds to different forest fuel beds. This will help define the need to establish different fuel management actions depending on the tree community. This work aimed to evaluate the fire spread, flame geometry, and consumption of the pine-fir and pine-oak litter layers in order to determine whether they correspond to the same fuel bed. Controlled burning of the litter layer was carried out on slopes of 0°, 10°, and 20°. Different fire behaviors were observed among tree communities (p<0.05) but without variation in fuel consumption. The propagation rate, flame length, flame height, and fire Index increased according to the slope, while the flame separation angle decreased. Litter load was positively correlated with flame height, flame length, and fire Index in pine-fir forest. Fitted models indicated that fire intensity increased exponentially with flame length and logistically with the fire spread. Heterogeneous fire behavior among tree communities suggests that they correspond to different fuel beds, with a significant influence of slope on fire behavior.

Keywords: Fuel bed, tree community, wildfire, fire spread, needle burning, Monarch Butterfly Biosphere Reserve

Resumen

La carga de combustibles, la topografía y la humedad del combustible influyen en el comportamiento del fuego. Conocer la relación de estos permite identificar el comportamiento del fuego según la comunidad arbórea, y si su heterogeneidad corresponde o no a diferentes camas de combustibles forestales, lo cual ayudará a definir la necesidad de establecer diferentes acciones de manejo de combustibles en función de la comunidad arbórea. El objetivo del presente trabajo fue evaluar la propagación del fuego, la geometría de la flama y el consumo de la capa de hojarasca de pino-oyamel y pino-encino para definir, si corresponden a la misma cama de combustible. Se realizaron quemas en condiciones controladas de la capa de hojarasca en pendientes de 0°, 10° y 20°. Se observó diferente comportamiento del fuego entre las comunidades arbóreas (p<0.05), pero sin variación en el consumo de combustibles. La velocidad de propagación, longitud y altura de la flama y el Índice del fuego aumentaron de acuerdo a la pendiente, mientras que el ángulo de separación de la flama se redujo. La carga de hojarasca se correlacionó positivamente con la altura y longitud de la flama e Índice del fuego en el bosque de pino-oyamel. Los modelos ajustados indicaron que la intensidad del fuego aumentó exponencialmente con la longitud de la flama y logísticamente en la propagación del fuego. El comportamiento heterogéneo del fuego entre las comunidades arbóreas sugiere que corresponden a diferentes camas de combustibles, con influencia significativa de la pendiente en el comportamiento del fuego.

Palabras clave: Cama de combustible, comunidad arbórea, incendio forestal, propagación del fuego, quema de acículas, Reserva de la Biosfera Mariposa Monarca.

Introduction

A forest fire is a non-structural and uncontrolled fire in an area with vegetation, caused by such factors as electrical discharges, volcanic activity, accidents, or anthropogenic causes (Miloua, 2019). These fires impact the surrounding ecosystem (Matsypura *et al.*, 2018) with magnitudes depending on the fire regime, topography, atmospheric conditions, and vegetation adaptation to fire (Francos *et al.*, 2018). Despite its adverse consequences, fire is an integral part of the ecosystem, generating both negative and positive effects on the flora and fauna (Matsypura *et al.*, 2018).

The interaction between topography, weather, and forest fuel plays a crucial role in the behavior of wildfires (Cochrane, 2009). In particular, the litter layer, composed of a variety of fuels, has captured the attention of researchers because of its impact on fire spread and fuel consumption (Cruz *et al.*, 2013). Therefore, understanding the factors that influence this process is essential to develop effective fire management and suppression strategies.

The complexity of the elements that determine the fire behavior in the litter layer lies in its physical, chemical, and flammability characteristics (Morgan *et al.*, 2015). Its physical characteristics exert an influence on litter layer aeration (Kauf *et al.*, 2018) and, according to the variability in tree composition, on the existence of different fuel beds (FB), the creation of different scenarios for fire behavior (Cornelissen *et al.*, 2017; Grootemaat *et al.*, 2017), and fuel consumption.

Fuel consumption depends on the behavior of the fire and is an indicator of its effects. The first to be consumed are light fuels (Fernandes and Loureiro, 2013), as they require less heat to ignite (Cornelissen *et al.*, 2017).

The objective of this research was to evaluate the fire behavior and the consumption of the needle litter layer in two tree communities of the Monarch Butterfly Biosphere Reserve (MBBR), as well as to adjust equations that explain the fire behavior and indicate if the tree communities correspond to the same FB. It is hypothesized that the pine-oak and pine-fir litter layers have different fire behaviors and fuel consumption, indicating that they correspond to different FBs. In addition, it is postulated that slope determines fire spread and intensity, given that the Wildland-Urban interface Fire Dynamics Simulator (WFDS) program has determined that the slope influences fire behavior (Pérez-Ramírez *et al.*, 2017; Sánchez-Monroy *et al.*, 2019).

This approach aims to contribute to a detailed understanding of the conditions affecting fire behavior in the litter layer in order to provide specific recommendations for context-specific management and thereby provide practical tools for effective planning and management of fuels management and wildfire suppression.

Materials and Methods

Fuel bed design

Litter samples were randomly collected from thirty-six square meter sample plots, composed of needles of the pine-fir (*Pinus* sp.-*Abies religiosa* (Kunth) Schltdl. & Cham.) and pine-oak (*Pinus* sp.-*Quercus* sp.) tree communities of the MBBR. The communities have a density of 284 and 412 trees ha^{-1}, height of 22.1 and 18.1 m (model Laser Forestry Pro Nikon® hypsometer), a normal diameter of 37.6 and 27.6 cm (model 347D Forestry Suppliers® diametric tape), and a crown diameter of 7.7 and 6.8 m (model TF50ME Truper® measuring tape), respectively. For each sample, the thickness of the litter layer was measured using a model F604 Office Depot® 30 cm ruler. The product was then collected in a labeled Kraft paper bag, and the wet weight was obtained with a model PTS3000 Pesola® scale.

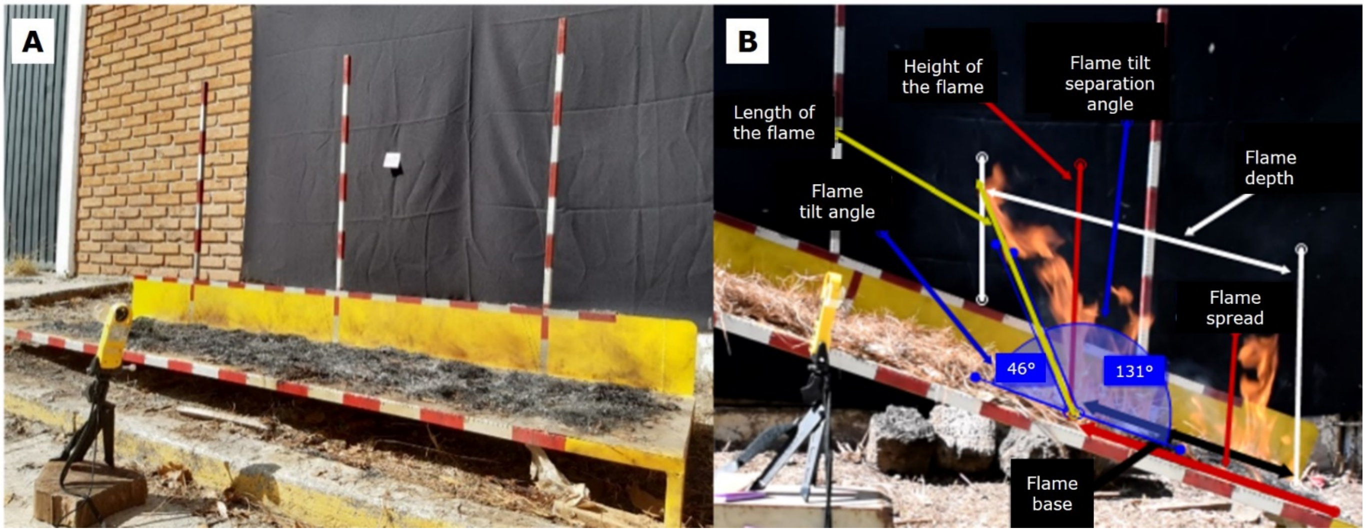
The samples were transported to the Institute for Research in Ecosystems and Sustainability (*Instituto de Investigaciones en Ecosistemas y Sustentabilidad*, *IIES*) in *Morelia*, *Michoacán*, for drying in a Epr-01 NOVATECH® oven at 79 °C. Woody fuels and cones were omitted to identify the fire behavior exclusively for the litter layer because only fine fuels influence fire spread (Morandini *et al.*, 2013). After drying, the samples were weighed to determine their dry weight (Table 1) and calculate the bulk density by dividing the dry weight by the average thickness of the litter layer in the collection area (Morfin *et al.*, 2012).

Table 1. Average values of burned litter layer characteristics for each slope condition.

	Pine-oak			Pine-fir		
	0°	**10°**	**20°**	**0°**	**10°**	**20°**
***wPre* (kg m²)**	0.7 (0.1)	0.4 (0.2)	0.5 (0.2)	0.5 (0.2)	0.3 (0.01)	0.7 (0.3)
Thickness (mm)	14.4 (3.1)	13.5 (2.7)	10.8 (3.2)	10.9 (3.3)	14.8 (2.1)	15.0 (4.2)
***BD* (kg m³)**	4.9 (0.6)	2.8 (1.0)	5.3 (2.3)	4.4 (1.0)	2.2 (0.4)	4.7 (1.4)

wPre = Pre-burned fuel load; *BD* = Bulk density. The standard deviation is shown in parentheses.

A 225×50 cm heat-resistant metal platform was designed to evaluate the fire behavior using the methodology of Sikkink *et al.* (2017) with modifications (Figure 1A). The platform was placed 13 cm off the ground in an open area owned by the National Forestry Commission (*Conafor*) in *Morelia*, *Michoacán.* The The inclination of the platform was adjustable and made it possible to simulate three types of slope to be established (0º, 10º, and 20°). The height of the flame was measured using one-meter-high graduated poles placed at 20, 95, and 170 cm along the length of the platform. Perpendicular to the platform, a Nikon® D5300 digital camera was installed to record the flame propagation speed and geometry of each fire in real time (Figure 1B).



A = Fuel consumption after burning; B = Geometry and fire behavior.

Figure 1. Metal platform for burning forest fuels.

Fuel burning

A buffer area of pine needles was placed in the first 25 cm of the platform. After buffering, the collected litter layer was spread uniformly and compressed manually to ensure a homogeneous thickness similar to that observed in the field. The burns were conducted between January and February 2021, at 10 a. m. and 3 p. m., and were initiated using a match. Six replicates were performed for each slope condition to ensure consistency of results. The environmental conditions were not controlled. Thus, an average temperature of 29 °C, a relative humidity of 35 %, and a wind speed of 2.24 km h^{-1} were recorded with a model 3000 Kestrel® meter.

Fire behavior measurement

The open-access software Kinovea was used (Sánchez-Pay, 2018) to measure the flame geometry every 5 seconds in each recorded video. The rate of spread was determined as the time it took for the fire to travel through the 200 cm length of the litter layer; its intensity was calculated using Equation 1 proposed by Byram (1959). The difference in pre- and post-burn dry weight, including carbonized residues and ash generated, was considered in estimating the consumption. The burn efficiency was evaluated with the Burn efficiency factor (*BEF*), using the Equation 2 proposed by Russell-Smith *et al.* (2009):

$$I = HwR \qquad (1)$$

Where:

I = Fire intensity (kW m^{-1})

H = Combustion heat (18 608 kJ kg^{-1}=8 000 BTU lb^{-1})

w = Mass of litter consumed (kg m^{2})

R = Rate of spread (m min^{-1})

$$BEF = 1 - \frac{Mash}{Mfuel} \qquad (2)$$

Where:

BEF = Burn efficiency factor

Mash = Residual unburned litter load plus ash load

Mfuel = Pre-burned litter load

Data analysis

Normality and homogeneity of variance were assessed using the Lilliefors test (Drezner *et al.*, 2008) and the modified Bartlett's test (Arsham and Lovric, 2011), respectively. Where the assumptions were not met, they were converted to logarithms (Zar, 2010). To compare the fire geometry, the fire spread rate and the litter consumption between tree communities and slopes, an ANOVA was performed at a significance level of *α*=0.05. A Tukey post-hoc test was applied to identify significant differences.

In addition, the relationships between the geometric variables of flame, load, and consumption were explored using Pearson's correlation coefficient. Finally, fittings were made using exponential models to estimate the rate of spread (Equation 3) and intensity of the fire (Equation 4). This approach made it possible to obtain more detailed information on fire dynamics in connection with the variables studied. The analyses were performed with the R software version 4.0.3 (Rstudio Team, 2020).

$$ROS = aFL^{b}\ exp^{(-cFL)} \qquad (3)$$

$$FI = aFL^{b} \qquad (4)$$

Where:

ROS = Rate of spread

FL = Flame length

FI = Fire intensity

a, *b*, *c* = Fit predictors

Results

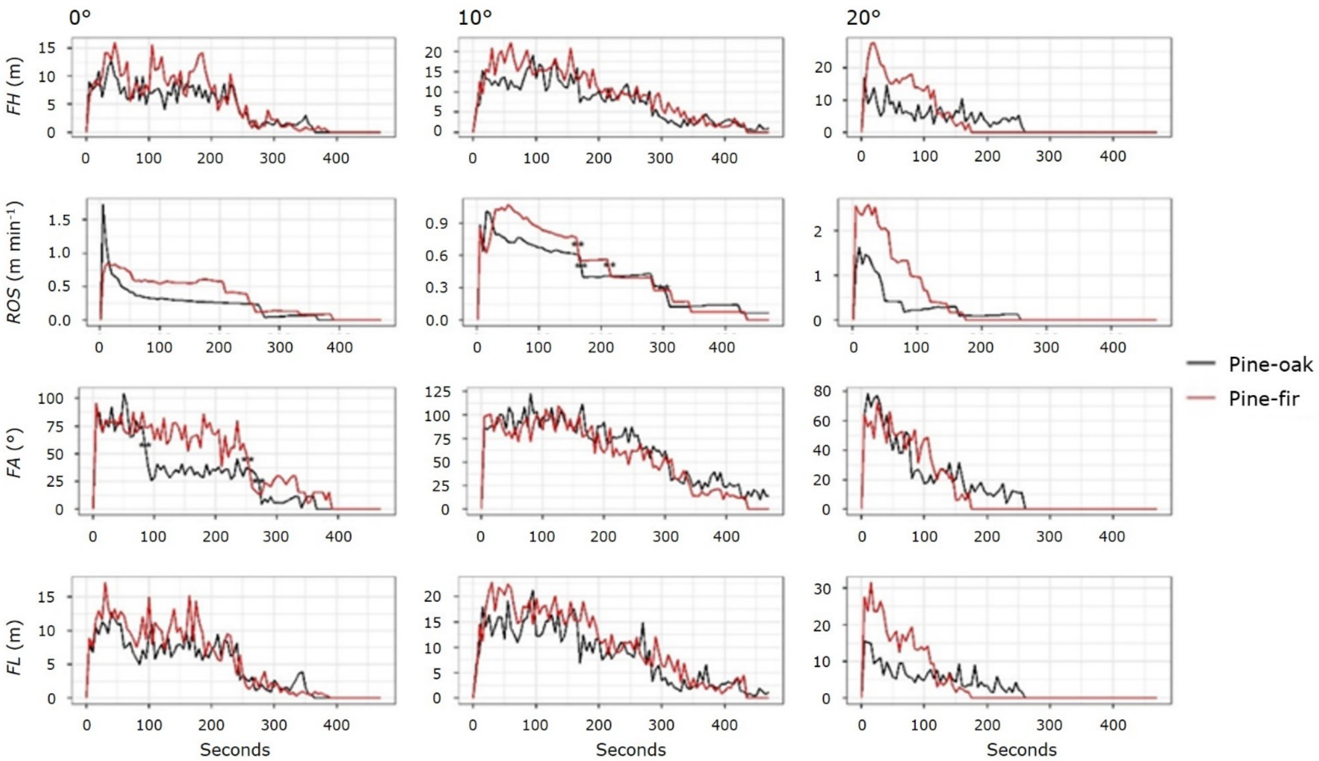
Fire behavior

The burning of the litter layer indicated that fire spread, flame height, and flame length in pine-oak was significantly higher than in pine-fir; propagation, flame geometric variables, and fire intensity increased according to the slope of the fire (Table 2). In both litter layers, the fire increased rapidly until it reached a peak and then decreased exponentially, except for the flame separation angle, which decreased with the pre-burned fuels (Figure 2). In conditions without slope, the rate of spread was slow and constant, while in the 20° slope the fire travel time decreased by one third compared to the 0° and 10° slope, and the flame angle was almost vertical.

Table 2. Fire behavior of burned litter layers.

Factor	*ROS* (m min^{-1})		*FH* (m)		*FL* (m)		*FA* (°)		*FI* (kW m^{-1})	
	***M* (*sd*)**	***p***	***M* (*sd*)**	***p***	***M* (*sd*)**	***p***	***M* (*sd*)**	***p***	***M* (*sd*)**	***p***
LL		0.021		0.029		0.025		0.185		0.168
PF	0.41 (0.31)	b	0.11 (0.08)	b	0.12 (0.07)	b	86 (16)		40.24 (51.84)	
PO	0.65 (0.48)	a	0.16 (0.08)	a	0.17 (0.08)	a	80 (14)		59.61 (49.01)	
φ		<0.001		0.053		0.039		<0.001		<0.001
0°	0.30 (0.18)	b	0.10 (0.07)	b	0.11 (0.06)	b	80 (13)	a	28.51 (25.27)	b
10°	0.43 (0.17)	b	0.14 (0.05)	ab	0.16 (0.06)	ab	90 (10)	a	31.69 (21.42)	b
20°	0.91 (0.53)	a	0.17 (0.10)	a	0.18 (0.10)	a	69 (13)	b	94.44 (68.85)	a
LL×φ		0.218		0.235		0.111		0.683		0.358

ROS = Rate of spread; *FH* = Flame height; *FL* = Flame length; *FA* = Flame angle; *FI* = Fire intensity; LL = Litter layer; φ = Slope; PF = Pine-fir; PO = Pine-oak; a, b, and c= Variation groups; *M* = Mean; *sd* = Standard deviation.



FH = Flame height; *ROS* = Rate of spread; *FA* = Flame angle; *FL* = Flame length; ** = Effect of samples turned off without reaching the end of the litter bed.

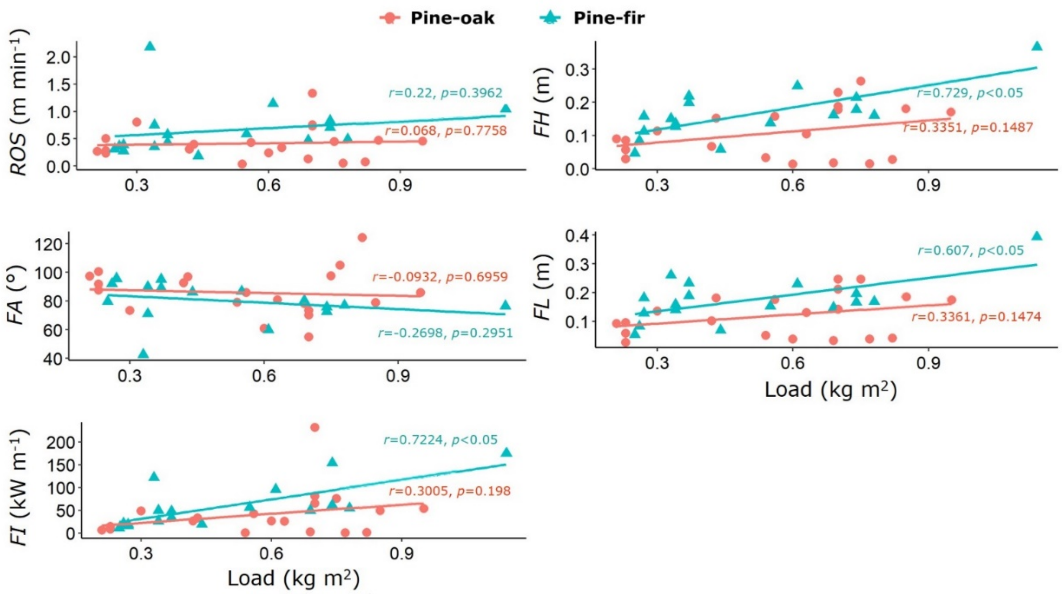
Figure 2. Fire behavior variables on three slopes *versus* time for pine-oak and pine-fir litter beds.

In both litter beds, slopes were significantly correlated with the rate of spread, while fire geometric variables had a considerable and significant correlation with the slope in pine-fir, unlike in pine-oak (Table 3). In pine-oak, the rate of spread was more intermittent, and the fire behavior was reduced, with islands of unburned litter. On the other hand, the load of pre-burned pine-fir litter was significantly correlated with the intensity of the fire, the flame height, and the flame length (Figure 3). In addition, pre-burned litter load and thickness and the flame geometry variables showed correlations with post-burn consumption and post-burn residue.

Table 3. Correlation of consumption, residue, and slopes with fire behavior.

	wPre	**Thickness**	***ROS***	***FL***	***FH***	***FI***	***FA***	**Consumption**	***BEF***	**Residue**
Consumption	0.77*	0.52*	0.69*	0.72*	0.77*	0.84*	0.26	-	-	-
Residue	0.59*	0.70*	0.66*	0.82*	0.83*	0.74*	0.54*	0.67*	-	-
φ PF	-	-	0.68*	0.73*	0.63*	0.63*	-0.46	0.08	-0.04	-0.03
φ PO	-	-	0.61*	0.16	0.23	0.44	-0.53*	0.25	0.28	0.18

wPre = Pre-burn load; *ROS* = Rate of spread; *FL* = Flame length; *FH* = Flame height; *FI* = Fire intensity; *FA* = Flame angle; *BEF* = Burn efficiency factor; φ = Slope; PF = Pine-fir; PO = Pine-oak; Residue = Carbonized residue; *p<0.05.



ROS = Rate of spread; *FH* = Flame height; *FA* = Flame angle; *FL* = Flame length; *FI* = Fire intensity.

Figure 3. Scatter plot and correlation coefficients for fire behavior in the evaluated litter layers.

Litter consumption

The pre- and post-burn litter load, litter consumption, charred residues, and *BEF* value did not vary according to tree communities (Table 4). However, the burns reduced the post-burn load, compared to the initial load: $F_{1.31}$=115.32, p<0.001. In the case of slope, it only influenced the pre- and post-burn litter load, with a greater reduction of these in the flat condition, where fire spread was slower, and was even similar on 20° slopes, where the height and length of the flame were greater.

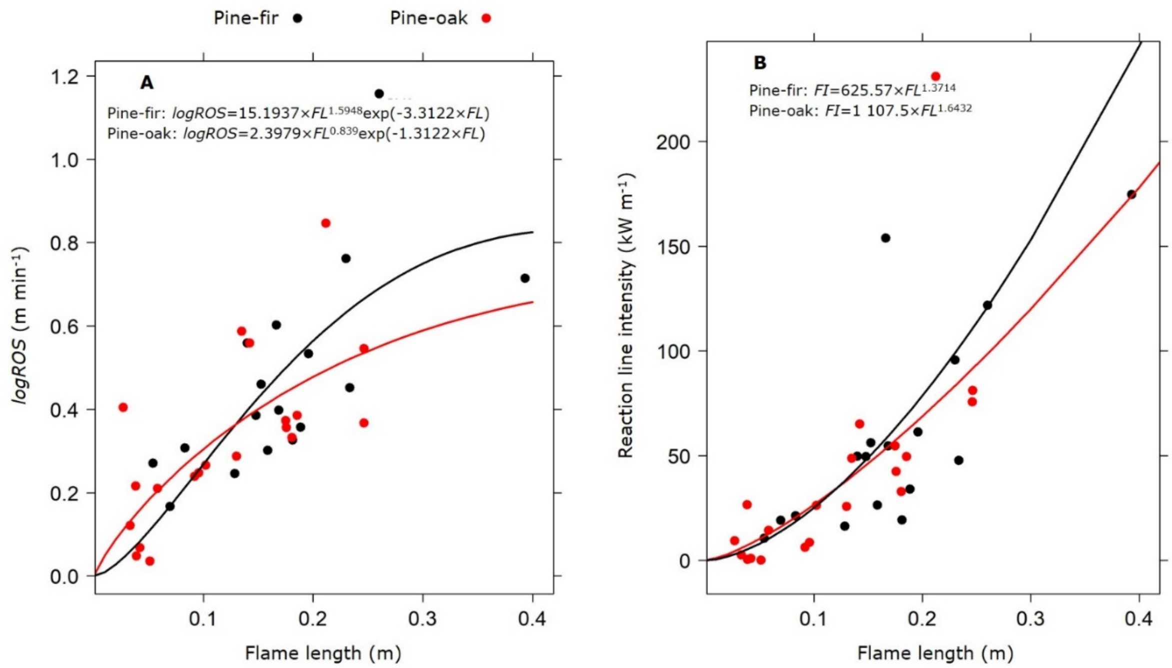
Table 4. Pre-burn and post-burn litter load and consumption variables.

Factor	*wPre* (kg m²)		*wPos* (kg m²)		Consumption (kg m²)		Residue (kg m²)		*BEF*	
	M (*sd*)	*p*	*M* (*sd*)	*p*	*M* (*sd*)	*p*	*M* (*sd*)	*p*	*M* (*sd*)	*p*
LL		0.562		0.113		0.309		0.774		0.055
PF	0.50 (0.25)		0.21 (0.16)		0.27 (0.13)		0.017 (0.009)		0.60 (0.14)	
PO	0.57 (0.43)		0.33 (0.22)		0.22 (0.15)		0.016 (0.017)		0.45 (0.25)	
φ		0.005		0.007		0.109		0.870		0.098
0°	0.61 (0.21)	a	0.38 (0.24)	A	0.22 (0.15)		0.017 (0.020)		0.40 (0.26)	
10°	0.37 (0.15)	b	0.14 (0.08)	B	0.20 (0.08)		0.018 (0.007)		0.57 (0.14)	
20°	0.63 (0.27)	a	0.30 (0.18)	Ab	0.32 (0.17)		0.015 (0.012)		0.50 (0.18)	
LL×φ		0.124		0.044		0.803		0.832		0.281

wPre = Pre-burn load; *wPos* = Post-burn load; Residue = Carbonized residue; *BEF* = Burn efficiency factor; LL = Litter layer; φ = Slope; PF = Pine-fir; PO = Pine-oak; a, b, and c = Variation groups; *M* = Mean; *sd* = Standard deviation.

Fire behavior regression

The rate of spread and fire intensity of leaf litter burns were significantly correlated with the flame length (r=0.91 and r=0.47, respectively). The fit of the rate of spread in relation to the flame length exhibited an r^2 of 0.38 in the two litter layers (Figure 4), while the fitting of the fire intensity with respect to the flame length registered an r^2 of 0.53 in pine-fir and 0.41 in pine-oak.



Fitting of: A = Logarithmic rate of spread (*logROS*); B = Intensity of fire as a function of the observed flame length. The red and black lines in the graphs correspond to the pine-oak and pine-fir litter layers, respectively.

Figure 4. Fitting of fire behavior prediction models for litter layer burns.

Discussion

Fire behavior

The burning of litter layers shows that the rate of spread, flame height, and flame length increase with the slope, and the tilt angle of the pre-burned fuels from the fire is reduced. This is consistent with the results of Sánchez-Monroy *et al.* (2019), who used the WFDS and obtained an unstable fire behavior on slopes of over 16°, with increased fire spread and flame tilt angle. Similarly, Pérez-Ramírez *et al.* (2017), who compared the results of simulations with the WFDS and needle burning, observed that the WFDS predicted scenarios within the range of fire spread obtained by burning. Thus, testing of litter layer samples has the potential to predict the fire spread.

Experimental burns show that slope influences the rate of spread and permanence of fire; these results are similar to those cited in needle burns and by the WFDS, which indicate that 150 seconds after ignition there are changes in the spread (Pérez-Ramírez *et al.*, 2017). Thus, on steep slopes, the propagation is twice as much as in areas with little slope due to the turbulence of the flame generated by the wind, which radiates more heat towards the pre-burned fuels (Morandini *et al.*, 2013; 2018).

For example, Tihay *et al.* (2014) and Yang and Chen (2018) note that radiation toward pre-burned fuels increases in 15° to 20° slopes and influences the rate of spread. In addition, the ignition of fuels is faster on steep slopes (Silvani *et al.*, 2018), increasing the risk of vertical fire advance and damage to the vegetation.

In experimental burns, the fire intensity is observed to grow in the first minutes until it reaches a maximum point and then stabilizes for a few seconds on 0° and 10° slopes, after which it decreases exponentially. This is consistent with the findings of Kreye *et al.* (2011) and Tihay *et al.* (2014). The reduction of the fire in the last seconds is due to the lack of fuel in front of the fire line, which reduces the convective heating, leaving only the flame generated by the slow combustion of residues.

Not only the slope but also the fuel load influences fire intensity; likewise, in areas with high litter load, the flame height and flame length increase (Kreye *et al.*, 2014) forming a V-shaped distortion on the fire line, as documented by Pérez-Ramírez *et al.* (2017) in pine needle burning.

The size of the fuels is important because of the time it takes to initiate the ignition process. Due to the porosity and sensitivity to convection, light fuels such as pine needles facilitate the spread of fire without penetrating deeply: only the superficial part is burned (Morandini *et al.*, 2018). This happens because of the physical characteristics of light fuels that allow aeration of the litter layer and abrupt change of the fire behavior with a short time exposure to variable weather conditions (Kauf *et al.*, 2018).

Heterogeneous layers of leaf litter, such as pine-oak, unburned islands generate large areas that favor the flora and fauna, as they serve as a refuge or as seed production and dispersal areas after a forest fire (Meddens *et al.*, 2018). Therefore, fire behavior is a function of the characteristics of the litter layer present in the tree communities.

Fuel consumption

Burned litter load and consumption were correlated, suggesting that greater consumption is expected in areas with a higher accumulation, as shown by Ottmar *et al.* (2016). In the present study, the consumption was lower than that recorded in experimental burns in pine forests of Portugal (Fernandes and Loureiro, 2013) and the Southwestern United States of America (Yokelson *et al.*, 2013). The lack of variation in consumption between litter layers could be because only the load within a square meter was burned. However, standard loading for all the samples would probably exhibit variation, since the higher the load, the higher the fire behavior and consumption.

The research documented here did not consider downed woody material (DWM) or shrubs. However, Brewer *et al.* (2013) determined that DWM consumption varies by size, with greater residue in areas with DWM>7.6 cm, as large DWMs are not fully consumed. If they do catch fire, the flame length, the energy released, and the hot gases increase. Moreover, the presence of shrubs increases flame length and fire intensity and there is greater canopy damage, a crown fire is initiated, and tree mortality increases (Silvani *et al.*, 2018; Varner *et al.*, 2021). Considering only the consumption of the litter layer is not enough to suggest whether or not several tree dominances correspond to the same FB; therefore, it is also important to incorporate fire behavior.

Fire spread and intensity fittings

The equations indicate that increasing flame length augments fire spread and fire intensity. The rapid increase in the litter layer of pine-fir compared to pine-oak may be because it is made up mainly of long needles that generate twice the temperature of layers without needles (Ellair and Platt, 2013). In contrast, in pine-oak forests, oak leaves are less flammable than pine needles and produce a shorter flame length (Kreye *et al.*, 2020). Thus, litter heterogeneity allows for variation in ignition and flame duration.

The intensity of the fire responded to the length of the flame, being greater in pine-fir. However, it is important to consider that the burns were carried out in closed areas with little influence of the atmospheric conditions, which, if included and controlled, could change the fire behavior.

The equations obtained allow predicting the fire behavior as a function of the flame length generated by the litter layer. However, including shrubs and DWM will considerably influence the fire behavior, as it varies according to the type of vegetation (Rossa and Fernandes, 2018). This highlights the importance of generating equations that will include the load of all undergrowth strata to improve the fit (Cruz *et al.*, 2018). Likewise, it is essential to consider the variation in flammability and consumption of shrubs present in the tree communities (Morandini *et al.*, 2019). Therefore, the effect of the tree dominance and the flammability of the distributed species on the fire behavior makes it possible to determine whether they correspond to the same FB.

Conclusions

The fire behavior, unlike the fuel consumption, varies according to burning of the litter layer of the pine-oak or the pine-fir tree communities, since the thickness and continuity of fuels influence the permanence of the fire. The slope affects the flame length and tilt by increasing the rate of spread of the fire in the litter layer of pine-fir, compared to that of pine-oak. The results suggest that the pine-fir and pine-oak tree communities produce different fuel beds. Burning fuels under manageable conditions makes it possible to obtain fire behavior data for areas where the use of fire is not allowed, as well as to generate fire behavior equations.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

Rubén Ortiz-Mendoza: experiment planning and development, statistical analysis, and drafting of the manuscript; Marco A. González-Tagle and Diego R. Pérez-Salicrup: supervision of the experimental design and revision of the document; Oscar A. Aguirre-Calderón, Wibke Himmelsbach and Luis G. Cuéllar-Rodríguez: revision of the manuscript.

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